Integrated Weed Management:

Explore the Potential

Integrated weed management: explore the potential

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Preface

Considerable recent research has been focussed on developing biologically and economically robust integrated weed management (IWM) systems. Growers are increasingly interested in IWM because of the escalating problem of herbicide resistant weeds, low commodity prices, and rising unease with the environmental and human health effects of pesticides. However, grower interest has not translated into widespread adoption of IWM systems. Of the numerous reasons for slow adoption of IWM most relate to avoidance of real or perceived risk. Farmers are concerned that changing management practices to implement IWM systems will reduce crop production or income and result in greater densities of troublesome weeds. This concern is compounded by the need for short-term profitability in the present economic climate. Farmers are understandably reluctant to accept reduced income or to forego income in one year, even if it means increased income in subsequent years.

There is a clear need for greater discussion on the extent and limitations of current knowledge of IWM systems, and how best to extend that knowledge to the agricultural community. Thus, the Expert Committee on Weeds (Canada) hosted a symposium entitled Integrated Weed Management: Explore the Potential at their annual meeting in November, 2000. This monograph contains the papers presented at that symposium.

Topics addressed were: a) the importance of developing both short- and long-term programs for improved management of weeds and the need for increased knowledge of weed biology and ecology, b) the level of weed resistance in Canada and how IWM may reduce or prevent further development of weed resistance, c) successful techniques used to extend information on IWM systems to Australian growers, d) the adoption of Pesticide-Free Production systems as a reason for growers to implement IWM, e) the successful economic implementation of IWM systems in barley, f) the challenges of implementing IWM in canola, g) approaches farm advisors could use to extend IWM information to producers, h) the challenges agrochemical companies face in positioning their products in IWM systems, and i) a grower's perspective on making IWM systems work at the farm level.

We hope the reader finds the information in this monograph to be thought provoking. There remains much work to be done by all members of the agricultural community to facilitate widespread adoption of IWM in the near future. Collectively, we can meet the challenge.

Robert E. Blackshaw and Linda M. Hall

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Contents

Herbicide resistance in Canada – where are we today?

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This review summarizes the current status of herbicide-resistant (HR) weed biotypes in Canada, identifies herbicide-use patterns and cropping systems that influence the selection of resistance, estimates the impact of HR crops on selection of HR weeds and as HR volunteers, predicts the potential for introgression of HR genes into weeds, and outlines strategies for managing herbicide resistance in weeds in Canada. Biotypes of wild oat (*Avena fatua* L.) resistant to acetyl-CoA carboxylase inhibitors in the prairie provinces, and biotypes of common chickweed [*Stellaria media* (L.) Vill.] and kochia [*Kochia scoparia* (L.) Schrad.] in western Canada and pigweed (*Amaranthus*) species in Ontario resistant to acetolactate synthase inhibitors are most abundant and widespread. Evolution of resistance in these biotypes is attributable to frequent use of herbicides from these two groups and the ease of selection by these modes of action. Increasing incidence of wild oat populations with multiple-group resistance will threaten the future effectiveness of herbicides of different groups. Herbicide-resistant crops can slow the selection of HR weeds by increasing crop and herbicide rotation options. However, potentially frequent use of herbicides in such crops may select for new HR weed biotypes. Evolved weed resistance due to selection pressure in HR crops is a more important risk than increased invasiveness of HR crops or introgression of HR traits into genomes of related weed species. Management of HR crop volunteers generally will be more difficult than for non-HR volunteers. Proactive or reactive management for herbicide resistance in weeds must consider the relative risks of herbicides of different modes of action to select for resistance and the differing propensity of herbicides to be metabolized in HR biotypes when rotating among herbicides, must meet basic criteria for effective herbicide mixtures, and should incorporate

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agronomic practices in cropping systems that help reduce weed seed production and spread.

Introduction

> "Pesticides often leave the most resistant pests behind … then … the resistant pests multiply … soon, enormous quantities of pesticides are sprayed on the crops to kill just as many pests as were there when the process began. Only now the pests are stronger. And all the while, the quantity of pesticides to which we ourselves are exposed continues to increase."

This quote by former United States (U. S.) Vice-President Al Gore (Avery 1995) paints a pessimistic outlook for pest resistance evolution and management. However, during the past 30 years, herbicide-resistant (HR) weeds have been managed successfully by growers worldwide, primarily by the use of alternative herbicides. Important exceptions are multiple-group HR grass species that are controlled by few or no alternative herbicides.

To date, 235 HR biotypes (150 species) have been reported in 47 countries (Heap 2000a, b), with Canada reporting 35 HR biotypes. The number of HR biotypes varies according to herbicide group, which is defined by mode of action. Twenty-seven percent of biotypes are resistant to acetolactate synthase (ALS) inhibitors (Group 2) (Retzinger and Mallory-Smith 1997), 26% to photosystem II inhibitors (Group 5), 11% to photosystem I inhibitors (Group 22), 9% to acetyl-CoA carboxylase (ACCase) inhibitors (Group 1), 8% to auxinic herbicides (Group 4), with the remaining 19% of biotypes resistant to herbicides of other modes of action. Crop monoculture and reliance on the same herbicide or herbicide mode of action have been implicated in the overwhelming number of cases of selection for HR weeds. Most cases of field-selected herbicide resistance are conferred by a single gene with a high degree of dominance (Powles et al. 1997).

Herbicide resistance in western Canada was last reviewed in 1993 (Morrison and Devine 1994). The purpose of this review is to summarize the current status of HR biotypes in Canada. We will identify herbicide-use patterns and crop rotations that influence the selection of herbicide resistance. HR crops alter cropping and herbicide-use patterns. Their impact on selection of HR weeds and as HR volunteers will be estimated, along with the potential for introgression of herbicide resistance genes into weeds. Lastly, prognostications are provided on the outlook for managing herbicide resistance in weeds in Canada.

Weed resistance in Canada

Group 1: ACCase inhibitors

Group 1 herbicides, which include two chemical families, the aryloxyphenoxypropionates (APP) and cyclohexanediones (CHD), have been widely used since their introduction in the late 1970s and early 1980s. A high intensity of Group 1 herbicide use was initially documented in regions of Manitoba (Bourgeois and Morrison 1997a). One-half or more of the sprayed acreage across the prairies annually received a Group 1 herbicide application in the mid-to-late 1990s (Beckie et al. 1999c).

Resistance in wild oat and green foxtail [*Setaria viridis* (L.) Beauv.] was first reported in Manitoba in 1990 and 1991, respectively (Heap and Morrison 1996; Heap et al. 1993; Morrison and Devine 1994). Resistance in wild oat was attributed to an altered target site, ACCase (Shukla et al. 1997a), conferred by a single, semidominant, nuclear gene (Murray et al. 1995), similar to the majority of cases of ACCase inhibitor resistance in grass weeds (Sinclair et al. 1999; Smeda et al. 2000). Resistance in *Avena* spp. to Group 1 herbicides has also been attributed to enhanced metabolism (Cocker et al. 2000), or to both target site and enhanced metabolism in populations in the United Kingdom (U. K.) (Coleman et al. 2000) and Australia (Maneechote et al. 1997).

Incidence of APP resistance in wild oat and green foxtail is markedly higher than CHD resistance (Beckie et al. 1999b, c, 2001; Seefeldt et al. 1994). Binding of APP herbicides may be more sensitive to changes in ACCase than binding of CHD herbicides (Bourgeois et al. 1997a). However, the earlier introduction of APPs may also have influenced the type of ACCase mutation selected (Devine 1997; Légère et al. 2000). Bourgeois et al. (1997a) identified three cross-resistance types: Type A – high APP, no or low CHD resistance; type B – low to moderate APP and CHD resistance; and type C (most common) – high APP and CHD resistance. In foxtail spp., a high level of resistance to sethoxydim and lower levels of resistance to APPs and other CHDs were determined (Heap and Morrison 1996; Shukla et al. 1997b). Resistance levels and cross-resistance patterns are related to a specific point mutation that presumably differentially influences herbicide binding to the target site (Devine 1997; Murray et al. 1996). For example, the point mutation of the ACCase gene conferring the cross-resistance pattern in the green foxtail biotype investigated by Heap and Morrison (1996) and Shukla et al. (1997b) was identified (Zhang and Devine 2000). Cross-resistance patterns may not be predicted from herbicide-use patterns. In a risk-assessment study, resistance to CHD herbicides was not related to CHD use but to frequency of ACCase inhibitor use (i.e., CHD plus APP), suggesting that the pressure imposed by APPs contributed to the selection of CHD resistance in wild oat (Légère et al. 2000). The presence of patches with different cross-resistance patterns within a field (Andrews et al. 1998; Bourgeois et al. 1997a) illustrates the difficulty in delaying or managing Group 1-HR wild oat by alternating APPs and CHDs in a field.

Surveys conducted across the three prairie provinces in 1996 and 1997 indicated that wild oat resistance to Group 1 herbicides occurred most frequently relative to other herbicide groups (Beckie et al. 1999c, 2001). Frequency of Group 1-HR wild oat was directly related to frequency of Group 1 herbicide use, similar to that noted by Bourgeois et al. (1997b). Group 1-HR wild oat occurred in approximately one-half of fields surveyed in each of the three prairie provinces. In Saskatchewan, it was estimated that 2.4 million ha were infested with Group 1-HR wild oat. In a high-risk township (annual Group 1 use in ≥50% of fields between 1981 and 1993) in Manitoba, two-thirds of the 30 fields surveyed in 1993 had Group 1-HR wild oat (Bourgeois and Morrison 1997b). None of the growers were aware of a resistance problem in the surveyed fields. Crop rotations had little influence on use patterns, because Group 1 herbicides are registered for use in cereal, oilseed, and pulse crops (Légère et al. 2000), which dominate cropping systems in the prairies. Resistance of grass weeds to ACCase inhibitors typically evolves to noticeable levels after six to ten applications.

Similar to wild oat, resistance in green foxtail to Group 1 herbicides is prevalent in Saskatchewan. A field survey conducted in 1996 determined that one in every 20 fields (1 million ha) had Group 1-HR green foxtail; in a 1997 survey, 83% of elevators had screenings, which originated from fields located within the service area, containing seeds of this HR biotype (Beckie et al. 1999b). Group 1-HR green foxtail in Manitoba is likely more abundant and widespread than in Saskatchewan because of the greater relative abundance of this species combined with greater Group 1 herbicide use.

As the frequency of occurrence of Group 1 resistance increases, there are more opportunities for pollen and seed movement to influence occurrence, in addition to selection. Green foxtail is highly self-pollinating (Jasieniuk et al. 1994). Wild oat is primarily self-pollinating, however, outcrossing rates up to 12% have been documented (Imam and Allard 1965; Murray 1996). Hence, HR green foxtail and wild oat are more likely to spread by seed via machinery or non-composted manure than by pollen. Wild oat can spread greater than 150 m by a combine harvester (Shirtliffe et al. 1998). Spread of resistance among wild oat (*Avena* spp.) patches within 350 m of each other was documented in the U. K. (Cavan et al. 1998). In western Canada, seed spread of HR wild oat and green foxtail within and among fields has been documented (Andrews et al. 1998; Beckie et al. 2001; Li et al. 2000). Management practices that limit the spread of HR seed can slow the occurrence of resistance. In the 1996 field survey in Saskatchewan, growers who reported practicing weed sanitation (e.g., cleaning harvesting and tillage equipment when moving between fields, tarping grain trucks, mowing or spraying ditches or uncontrolled weed patches, etc.) were less likely to have HR wild oat than those who were less careful (Légère et al. 2000).

Group 2: ALS inhibitors

Group 2 herbicides are non-competitive inhibitors of ALS, the first enzyme common to the biosynthesis of the branched-chain amino acids (Thill and Mallory-Smith 1996). They include five chemical families: sulfonylureas (SU), imidazolinones (IMI), triazolopyrimidines (TP), pyrimidinyl thiobenzoates (PB), and sulfonylaminocarbonyltriazolinones (e.g., flucarbazone-sodium).

Even though ALS inhibitors were introduced relatively recently (1982), the greatest number of reported weed biotypes are resistant to this herbicide group (Heap 2000a, b). In most cases, resistance is conferred by a single, semidominant, nuclear gene and is endowed by modification of the target site by multiple point mutations (Subramanian and Bernasconi 1996). The gene encoding ALS has been sequenced and changes that confer resistance have been identified and mapped. Varying levels of resistance and cross-resistance patterns have been associated with specific regions or domains, and different amino acid substitutions result in quite predictable patterns of cross-resistance (Foes et al. 1999). For example, proline changes in Domain A of ALS likely are responsible for the high level of insensitivity to SU and TP herbicides and moderate to low level of resistance to IMIs (Devine et al. 1991; Guttieri et al. 1995; Horsman and Devine 2000). Similar to ACCase inhibitor resistance, patterns of cross-resistance cannot be predicted based on field histories and must be assessed for each population (Poston et al. 2000).

In western Canada, ALS inhibitor resistance has been documented in eight broadleaf weed species: multiple populations of common chickweed since 1988 in central Alberta (Morrison and Devine 1994; O'Donovan et al. 1994a), a biotype of Russian thistle [*Salsola pestifer* (A.) Nels.] in 1989 in Saskatchewan (Morrison and Devine 1994), a biotype of common hempnettle (*Galeopsis tetrahit* L.) in 1995 in Manitoba (Heap 2000a), a biotype of false cleavers (*Galium spurium* L.) in 1996 in Alberta (Hall et al. 1998), two biotypes of spiny annual sow-thistle [*Sonchus asper* (L.) Hill] in 1996 and a ball mustard [*Neslia paniculata* (L.) Desv.] biotype in 1998 in Alberta (Heap 2000a), and a biotype of wild mustard (*Sinapis arvensis* L.) in 1992 in Manitoba and in 1993 in Alberta (Heap 2000a; Jeffers et al. 1996). In the latter HR biotype, a high level of resistance to ethametsulfuron and low level of resistance to metsulfuron was attributed to enhanced cytochrome P450 oxygenase activity (Hall et al. 1999; Veldhuis et al. 2000). This was the first report of metabolism-based resistance in a broadleaf weed to a SU herbicide. Kochia HR biotypes have been reported since 1988 in the three prairie provinces (Morrison and Devine 1994). Over 50 populations of ALS-HR kochia have been documented in southern Saskatchewan and southern Alberta during the past five years (H. J. Beckie; L. M. Hall, unpublished data). Gene flow through pollen and seed movement markedly aids in the dispersal of resistance in this species (Mallory-Smith et al. 1993; Saari et al. 1994; Stallings et al. 1994).

Patterns of herbicide use have contributed to the selection for Group 2 resistance in broadleaf weeds. Resistance in broadleaf weeds typically develops after four to seven applications. In Alberta in 1995, 45% of cereal fields and 8% of canola fields received a Group 2 herbicide application. Group 2 herbicide use is higher in Alberta and Manitoba than in Saskatchewan (Figure 1).

In Ontario, failure of imazethapyr to control *Amaranthus* spp. was first noticed in 1996. Resistance, as determined by dose response analysis and comparison of GR_{50} values, was confirmed in eight Powell amaranth (green pigweed) [*Amaranthus powellii* (S.) Wats.] populations and four redroot pigweed (*Amaranthus retroflexus* L.) populations collected in southwestern Ontario in 1997 (Ferguson et al. 2000, 2001). Furthermore, cross-resistance to thifensulfuron was found in two populations of Powell amaranth and two populations of redroot pigweed. Resistance factors in HR Powell amaranth ranged between 174 and 3,438, whereas those for HR redroot pigweed varied between 33 and 168. Molecular analysis of the ALS gene from these different populations has been performed (K. McNaughton and F. J. Tardif, unpublished data). To date, three distinct mutations, Domain B, Domain C and Carboxy end, have been found in Powell amaranth HR biotypes (Table 1). The same three mutations, as well as a fourth one at Domain D, have also been found in redroot pigweed. There appears to be good agreement between the pattern of resistance found in those populations and the patterns reportedly conferred by these mutations. The occurrence of many different mutations in these two species indicates that selection had occurred independently in different locations simultaneously.

Selection occurred primarily in soybean (*Glycine max* L.) where reliance on ALS inhibitors had been fairly high in the 1990s. Imazethapyr dominated the soybean market for most of the 1990s. In 1997, more than 75% of the soybean crop in Ontario was treated with at least one ALS inhibitor, compared to over 30% of the corn (*Zea mays* L.) crop. In some regions of Ontario, growers have switched from a traditional corn, soybean and winter wheat (*Triticum aestivum* L.) rotation to near monoculture of soybean. This change in cropping system is due to a combination of factors that includes favorable prices for soybeans and a succession of years where the planting conditions have not been conducive for sowing corn. The net result is repeated use of ALS inhibiting herbicides in soybean, creating intense selection pressure for evolution of HR biotypes. In some cases resistance was found in fields that had relatively limited exposure to ALS inhibitors, suggesting that transport of seeds by harvesting machinery may play a role in the dissemination of the HR biotypes.

In grass weeds, Group 2 resistance in wild oat has been documented. Although no cases of Group 2 resistance in green foxtail have been discovered in western Canada, a biotype in the U. S. was reported in 1999 (Heap 2000a). In a systematic survey of fields in two randomly selected townships in 1997 (Beckie et al. 2001), 20 to 30% of fields had wild oat populations exhibiting Group 2

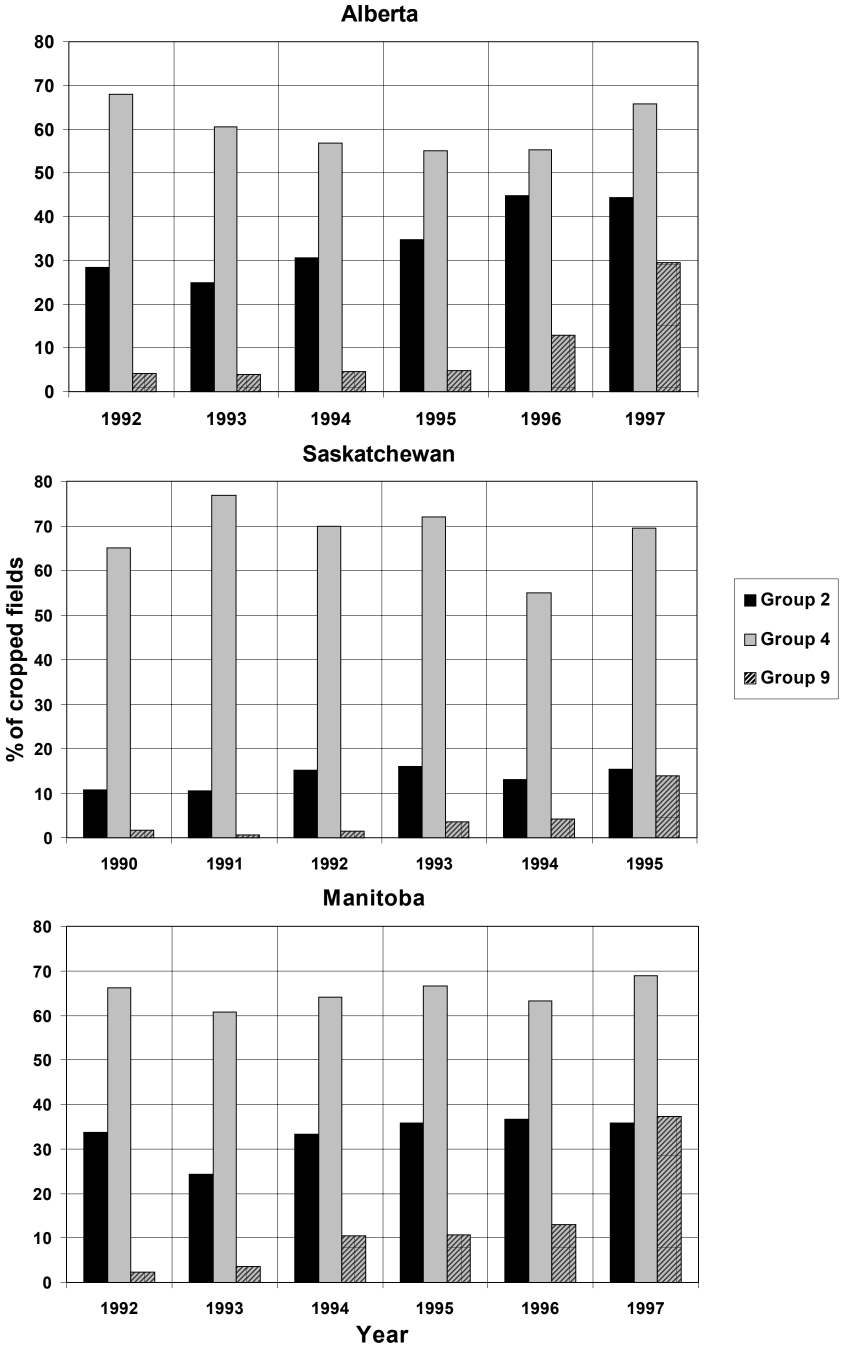


Figure 1. Percentage of cropped fields in Alberta, Saskatchewan, and Manitoba treated with Group 2, 4, and 9 herbicides (Source: A. G. Thomas, unpublished data).

Table 1. Resistance factors and type of mutation found in different ALS inhibitor-HR populations of *Amaranthus* spp. in Ontario.

Population	Resistance factor (HR/HS)[a] Imazethapyr	Resistance factor (HR/HS)[a] Thifensulfuron	Mutation
Powell amaranth (green pigweed)			
Harrow 1 (susceptible control)	1	1	none
Hullet 12	3.8	1	none
Southwold 24	4.2	0.33	none
Iona 20	174 *[b]	0.67	Carboxy end
Elma 4	251 *	1	Carboxy end
Brigden 36	657 *	na	Domain C
McKillop 9	769 *	0.33	Domain C
Brigden 30	916 *	2,416 *	Domain B
Brigden 33	1,059 *	na	Domain C
Brigden 29	1,284 *	1,257 *	Domain B
Brigden 39	3,438 *	0.33	Domain C
Redroot pigweed			
Lobo 13	0.05	5	none
Ekfrid 16	0.42	0.33	none
Elora 1 (susceptible control)	1	1	none
Mosa 17	1	na	none
Parkhill 15	13	1,104 *	Domain B
Caledonia 43	33 *	na	Domain C
Southwold 27	58 *	2	Carboxy end
Woodstock 46	95 *	0.83	Domain D
Parkhill 14	168 *	270 *	Domain B

[a] GR_{50} of herbicide-resistant (HR) biotype divided by GR_{50} of herbicide-susceptible (HS) biotype.

[b] *-denotes confirmed HR populations.

resistance. In another survey in the province that year, 23% of grain elevators had Group 2-HR wild oat (Beckie et al. 1999c). In Manitoba in 1997, 21% of cereal fields sprayed with imazamethabenz had Group 2-HR wild oat (Beckie et al. 1999c). The mechanism of resistance in these populations has yet to be identified, but resistance to ALS inhibiting herbicides in grasses is commonly due to metabolism (De Prado and Menendez 1996). The mechanism of imazamethabenz resistance in a wild oat biotype in North Dakota has been linked to uptake, translocation, and metabolism and not to an altered target site (Nandula et al. 2000). It was subsequently reported that the primary mechanism of resistance in this biotype was reduced metabolism of imazamethabenz-methyl to the biologically active imazamethabenz acid (Nandula and Messersmith 2000).

Group 3: Dinitroanilines

Despite extensive and sustained use of dinitroanilines in western Canada, only one weed species has biotypes with Group 3 resistance. Worldwide, only a few examples of resistance have been reported (Smeda and Vaughn 1994). Dinitroaniline resistance in green foxtail, discovered in 1988 in Manitoba (Morrison et al. 1989), typically developed after 15 to 20 applications. The persistence of trifluralin resistance between 1988 and 1995 in fields infested with HR green foxtail suggests no apparent fitness penalty (Andrews and Morrison 1997). In southwestern Manitoba, one in four fields is estimated to have dinitroaniline-HR green foxtail (Goodwin 1994). In a field survey in Saskatchewan in 1996, 11% of fields had Group 3-HR green foxtail; two-thirds of those fields were located in the Parkland region where frequency of fields with this weed species is highest (Beckie et al. 1999b).

In contrast to green foxtail, incidence of Group 3-HR biotypes of wild oat is rare. No resistance was detected in populations in high-risk fields in Saskatchewan in 1996. Recently, however, a biotype resistant to pronamide in the U. S. has been reported (Heap 2000a). The mechanism of resistance in green foxtail has yet to be completely elucidated. Dinitroanilines inhibit mitosis by binding to tubulin, a component of microtubules. HR goosegrass [*Eleusine indica* (L.) Gaertn.] contains an altered tubulin that reduces herbicide binding (Anthony et al. 1998; Baird et al. 1996). An altered microtubule-associate protein (MAP) has been proposed to confer resistance in green foxtail (Smeda et al. 1992). In both autogamous species, a single, recessive, nuclear gene confers resistance (Jasieniuk et al. 1994; Zeng and Baird 1997).

Group 4: Auxinic herbicides

Although synthetic auxinic herbicides have been used frequently since 1946 (e.g., Figure 1), there are relatively few reports of resistance to these compounds (Coupland 1994). Resistance typically evolves after 15 to 30 applications. The slow evolution of resistance in weed biotypes to auxinic herbicides has been attributed to the lack of a single target site (Coupland 1994), low selection pressure (efficacy, persistence), or an unusually low rate of mutation of the locus conferring resistance or alternatively, most mutations at this locus may be lethal (Debreuil et al. 1996; Jasieniuk et al. 1995). In 1990, populations of wild mustard resistant to dicamba, 2,4-D, MCPA, dichlorprop, mecoprop, and picloram were discovered in west-central Manitoba, after selection with a mixture of MCPA, mecoprop, and dicamba for 10 consecutive years in addition to auxinic herbicides used previously (Heap and Morrison 1992). Reduced binding to auxin-binding protein(s) (ABP) is the probable basis for resistance in this biotype (Deshpande and Hall 2000; Webb and Hall 1995), similar to a mecroprop-HR common chickweed biotype in the U. K. (Barnwell et al. 1989). Differences were observed between HR and susceptible (HS) biotypes in amino acid sequences in DNA encoding ABP(s) (Hall and Zheng 2000). Calcium may mediate resistance in this biotype (Wang et al. 2001). In other auxinic HR biotypes, enhanced metabolism is usually the basis of resistance (Coupland 1994). Resistance to dicamba in the HR biotype of wild mustard from Manitoba was conferred by a single, completely dominant, nuclear allele (Jasieniuk et al. 1995). This simple inheritance, which facilitates rapid resistance evolution, was not expected because of the low incidence of HR biotypes despite long-term and widespread use of these herbicides. In 1998 in Alberta, a common hempnettle biotype resistant to dicamba and MCPA was reported (Heap 2000a). In North Dakota, numerous auxinic-HR kochia biotypes have been reported; gene flow likely contributed significantly to the large number of HR populations (Manthey et al. 1997).

Wild carrot (*Daucus carota* L.) with evolved resistance to 2,4-D within 5 years of continuous use, was discovered along a roadside near Milton, Ontario in 1957 (Switzer 1957). This occurrence was one of the first recorded cases of herbicide resistance in weeds. In 1998, seeds were collected along the same roadside and the persistence of resistance in the population was confirmed (Van Eerd et al. 2000).

Group 5: Photosystem II inhibitors (triazines)

In western Canada, a common groundsel (*Senecio vulgaris* L.) population resistant to triazine herbicides was reported in British Columbia in 1978 (LeBaron 1985). In 1994, a metribuzin-HR biotype of wild mustard was found in a field in southern Manitoba where metribuzin had been applied frequently (L. F. Friesen, personal communication). While the mechanism has not yet been examined, it is likely that it is target site-based.

The greatest number of weed biotypes in eastern Canada are resistant to the triazines. Stephenson et al. (1990) have reviewed the evolution of triazine resistance in relation to agronomic practices. Resistance to the triazines was first documented in common lambsquarters (*Chenopodium album* L.) in 1974 in Ontario. Since then, a total of 10 species have evolved triazine-HR biotypes in the province. Resistance to triazines has also been found in Quebec (G. D. Leroux and D. Bernier, personal communication) and in the Maritime region (M. G. Sampson, personal communication). Of all the species in Ontario, common lambsquarters and *Amaranthus* spp. have spread the most, causing the most concern to crop managers. Although the exact mechanism has not been elucidated, it is likely that resistance is due to a serine to glycine substitution in the D1 protein of photosystem II due to a point mutation in the *psbA* gene that reduces herbicide binding, similar to the vast majority of triazine resistance cases worldwide. This mutation confers a high level of resistance to the triazines and moderate resistance to triazinones, but little or no resistance to phenylureas (Gronwald 1994). The target site mutation reduces photosynthetic efficiency, which is often manifested by decreased plant productivity and competitiveness (i.e., reduced fitness).

Triazine resistance was an issue of greater importance in the 1980s than now. At that time, corn was grown as a monoculture with high rates of atrazine and little tank mixing with other broadleaf weed herbicides. Triazine resistance is no longer a major preoccupation for growers and crop managers. The reliance on atrazine has been reduced due to the prevalence of soybean as a rotational crop with corn and the availability of alternative herbicides. Atrazine is still being used, but seldom alone and at much lower rates than in previous decades. Thus, selection pressure has been reduced and HR biotypes are being controlled successfully. Because of the long seedbank life of species such as common lambsquarters, *Amaranthus* spp., and common ragweed (*Ambrosia artemisiifolia* L.), it is expected some level of triazine resistance remains. These biotypes remain unnoticed unless atrazine is used as the sole broadleaf weed herbicide. Their presence is still a concern, however, given the realistic possibility of the evolution of multiple resistance through sequential selection with herbicides having a different mode of action.

Group 7: Photosystem II inhibitors (phenylureas)

This group of herbicides, of which linuron is the most widely used in eastern Canada, has a similar mode of action as the triazines, but has a slightly different binding site and resistance is relatively rare compared to the triazines. Linuron is registered for use in a range of crops such as corn, edible bean (*Phaseolus vulgaris* L.), soybean, carrot, etc. Its use in field crops is now relatively limited, but in carrots it is one of the few broadleaf weed herbicides available.

Two distinct cases of linuron-selected resistance have recently been reported in eastern Canada from fields that were in carrot production. Common ragweed biotypes from southwestern Quebec have been reported to have developed linuron resistance (Saint-Louis et al. 2000). Survival of the HR biotypes occurred at rates much higher than the minimum lethal rate for the HS biotypes. A biotype of Powell amaranth originating from a carrot field north of Toronto, Ontario is resistant to linuron and has cross-resistance to some triazine herbicides. Dose-response analysis indicated approximately 7-fold resistance to linuron in the HR biotype compared to an HS biotype, and lower level of resistance to atrazine and prometryn (M. Dumont and F. J. Tardif, unpublished data). The number of fields affected as well as the spread of this biotype is unknown, but it would be expected that resistance is limited to fields where linuron was heavily used.

Group 8: Triallate and difenzoquat

In a long-term study, resistance in wild oat occurred after 18 years where triallate was applied annually in continuous wheat, but not where triallate was applied 10 times in a wheat-fallow rotation over the same period (Beckie and Jana 2000). The number of applications to select for resistance corresponded with estimates obtained from field histories of Group 8 herbicide use for 15 populations in Alberta that were confirmed to be resistant in 1990 (O'Donovan et al. 1994b). Triallate-HR biotypes are also resistant to the chemically unrelated herbicide difenzoquat, even through little history of use in infested fields in Alberta and Montana was evident. Most of these fields were under continuous monoculture barley or wheat production. In 1997, about 15% of fields and 24% of grain elevators in Saskatchewan and 19% of fields in Manitoba had Group 8-HR wild oat (Beckie et al. 1999c, 2001).

The mechanism of resistance is a matter of dispute. Elevated endogenous levels of gibberellins in HR biotypes, resulting in rapid shoot growth that precludes phytotoxic levels of the herbicides from reaching their site of action in the shoot meristem has been documented (O'Donovan et al. 1999b; Rashid et al. 1998) and proposed as a single mechanism responsible for triallate and difenzoquat resistance. Alternatively, resistance to triallate in biotypes in Montana is attributed to reduced metabolism of the proherbicide, triallate sulfoxide (Kern et al. 1996). Additionally, tight binding of difenzoquat to cell walls in HR compared to HS biotypes, preventing entry to the site of action in the chloroplast, was proposed to be responsible for difenzoquat resistance in these triallate-HR biotypes (Kern and Dyer 1998). However, the co-occurrence of triallate and difenzoquat resistance in all wild oat biotypes makes multiple mechanisms less likely.

There is little difference in fitness between HR and HS biotypes (O'Donovan et al. 1999a). However, seeds from HR populations are less dormant than those from HS populations, which may at least partially explain a general decline observed in the level of HR:HS wild oat from 1990 to 1997 in fields in Alberta (O'Donovan et al. 2000). However, most fields still contained high levels of HR wild oat, especially where triallate or difenzoquat was applied more than twice between 1988 and 1997. Greater and more rapid emergence of HR individuals compared to HS individuals, analogous to that of ALS-HR kochia biotypes (Dyer et al. 1993), may be potentially exploited for selective HR biotype control prior to seeding.

Group 9: EPSPS inhibitors

Glyphosate was commercially introduced in 1974 and is now one of the world's most widely used herbicides. Glyphosate is a competitive inhibitor of the plastidic enzyme 5-enolpyruvyl-shikimate-3-phosphate synthase (Subramanian et al. 1996). The paucity of reported cases of resistance to this herbicide may be due, at least partially, to few non-lethal mutations at the site of action (Gressel 1999). To date, only a few populations of rigid ryegrass (*Lolium rigidum* Gaudin) in Australia and California (Heap 2000a), goosegrass in Malaysia, and horseweed [*Conyza canadensis* (L.) Cronq.] in Delaware, U. S. (M. J. VanGessel, personal communication), have evolved resistance. In Australia, an HR biotype was found in a field in 1995 that was subjected to 10 applications over a 15-year period (Pratley et al. 1999), and in an orchard which received two to three applications per year for 15 years (Powles et al. 1998). Resistance is inherited as a single, semidominant, nuclear gene in annual ryegrass (Lorraine-Colwill et al. 2000). HR biotypes of goosegrass were discovered in an oil palm plantation in 1997, where glyphosate had been applied for 10 years. Mutation at the site of action confers resistance (Dill et al. 2000).

A survey of 53 no-till fields at high risk for glyphosate resistance (10 to 24 years of consecutive use) in the three prairie provinces in 1998 failed to detect glyphosate-HR biotypes (Table 2).

Table 2. Number of populations of weed species tested for glyphosate resistance in a survey of 53 no-till fields in Alberta, Saskatchewan, and Manitoba in 1998: all populations were not herbicide-resistant.

Species	Number of populations
wild oat, *Avena fatua* L.	77
green foxtail, *Setaria viridis* (L.) Beauv.	42
common lambsquarters, *Chenopodium album* L.	9
narrowleaf hawksbeard, *Crepis tectorum* L.	8
false cleavers, *Galium spurium* L.	5
Canada thistle, *Cirsium arvense* L.	4
redroot pigweed, *Amaranthus retroflexus* L.	4
kochia, *Kochia scoparia* (L.) Schrad.	3
wild buckwheat, *Polygonum convolvulus* L.	3
green smartweed, *Polygonum scabrum* Moench	2
common hempnettle, *Galeopsis tetrahit* L.	2
perennial sow-thistle, *Sonchus arvensis* L.	2
shepherd’s-purse, *Capsella bursa-pastoris* (L.) Medicus	2
field pennycress, *Thlaspi arvense* L.	2
dandelion, *Taraxacum officinale* Weber	1
foxtail barley, *Hordeum jubatum* L.	1

Group 22: Photosystem I Inhibitors (bipyridyliums)

Resistance to paraquat has been documented in horseweed and Virginia pepperweed (*Lepidium virginicum* L.) (Smisek et al. 1998). These HR biotypes occurred in fruit orchards in Essex County, Ontario where paraquat was used intensively (three to five times a year for at least 10 years) to control weeds between trees. The resistance level was about 30-fold in horseweed and 5- to 10-fold in Virginia pepperweed. Resistance in horseweed is conferred by a single, dominant, nuclear gene; in Virginia pepperweed, however, resistance is inherited in a more complex manner and polygenic control is believed to be involved (S. Weaver, personal communication). Because it appears that the populations have not spread from the affected orchards, resistance is contained. Growers have simply switched to using glyphosate to manage these HR populations.

Multiple-group resistance

Three wild oat populations in northwestern Manitoba in 1994 were discovered to be resistant to fenoxaprop-P (Group 1), imazamethabenz (Group 2), and flamprop (Group 25) (Friesen et al. 2000; Morrison et al. 1995). In a field survey in Saskatchewan in 1996, 20% of Group 1-HR populations were also resistant to ALS inhibitors, even though these herbicides were not used frequently (Beckie et al. 1999c). In a survey of two randomly selected townships in Saskatchewan in 1997, multiple-group resistance (1,2; 1,8; 2,8; 1,2,8) were exhibited in wild oat populations in 30 to 40% of fields in both townships (Figure 2) (Beckie et al 2001). In Manitoba in 1997, 27% of cereal fields surveyed had wild oat resistant to herbicides from more than one group; four populations were resistant to all herbicides registered for use in wheat (Groups 1, 2, 8, 25) (Beckie et al. 1999c). Similar to the multiple-group populations discovered in 1994, the fields had a history of Group 1 herbicide use only. An additional five quadruple-group HR populations from northwestern Manitoba have since been confirmed (H. J. Beckie, unpublished data).

Multiple-group HR wild oat biotypes are conferred either by a single, non-target site mechanism (e.g., enhanced metabolism), or multiple mechanisms selected sequentially with herbicides of different modes of action. Metabolism-based resistance is more probable where herbicide-use histories indicate little or no use of herbicides from one or more herbicide groups to which the biotype exhibits resistance. For example, the likely mechanism conferring multiple-group resistance in the wild oat biotypes from northwestern Manitoba is enhanced metabolism by cytochrome P450 oxygenases (Friesen and Hall 2000). Because the occurrence of multiple-group resistance in wild oat apparently is not rare and because HR populations are geographically separated, the mutation or mutations that confer such resistance also are not rare (Friesen et al. 2000). Metabolic resistance appears more frequently in monocot weeds and crops than in dicot plants (Werck-Reichhart et al. 2000). Herbicides that are not readily metabolized are unlikely to select for metabolism-based resistance. Herbicides that are detoxified via pathways different than that mediated by cytochrome P450 oxygenases or that are not metabolized will lessen the chance of selecting for multiple-group (metabolism-based) HR grass weed populations.

The evolution of individuals with multiple mechanisms of resistance is slower and less probable, particularly since wild oat is primarily self-pollinating. Based on a compounded resistance frequency model, the probability of HR mutants with multiple mechanisms of resistance (target site-based) in an unselected population is the product of the probabilities of resistance to each affected herbicide group and thus is rare (Wrubel and Gressel 1994). Frequent use of herbicides from different groups in a field over time can enrich HR populations with different resistance mechanisms; outcrossing between populations in close proximity that possess different HR mechanisms can result in plants with multiple resistance. Spread of HR seed within and among fields can also aid this process.

Group 1- and 3-HR green foxtail in Manitoba (Heap and Morrison 1996) and Saskatchewan (Beckie et al. 1999b) is likely due to two resistance mechanisms within individuals. HR biotypes were initially selected with Group 3 products; control of these HR biotypes with Group 1 herbicides selected for multiple-group HR biotypes (Heap and Morrison 1996). Similarly, resistance to ALS inhibitors and to the synthetic auxin, quinclorac, in a biotype of false cleavers is likely due to two mechanisms. ALS resistance in this biotype is due to target site insensitivity, whereas the mechanism of quinclorac resistance is unknown (Hall et al. 1998).

Given the prevalence of triazine resistance in Ontario and the recent heavy reliance on Group 2 herbicides, it was reasonable to anticipate that multiple-group HR populations of *Amaranthus* spp. could evolve as a result of sequential selection. A growth room screen of 40 populations of *Amaranthus* spp., including those previously known to be resistant to ALS inhibitors, revealed the existence of one Powell amaranth population with triazine and imazethapyr resistance (Ferguson et al. 2000). Population ‘Elma 4’ was found in Perth County, an area known for mixed agriculture, diverse rotations, and a high percentage of dairy farms. High level resistance to atrazine was confirmed, with a lower level of resistance to metribuzin, a triazinone herbicide. Treatment of this population in the greenhouse with mixtures of imazethapyr plus atrazine or imazethapyr plus metribuzin had no visible affect on HR individuals. Triazine resistance in this population is conferred by a mutation in the *psbA* gene (R. S. Diebold and F. J. Tardif, unpublished data), whereas imazethapyr resistance is due to Carboxy-end mutation in the ALS gene (K. McNaughton and F. J. Tardif, unpublished data).

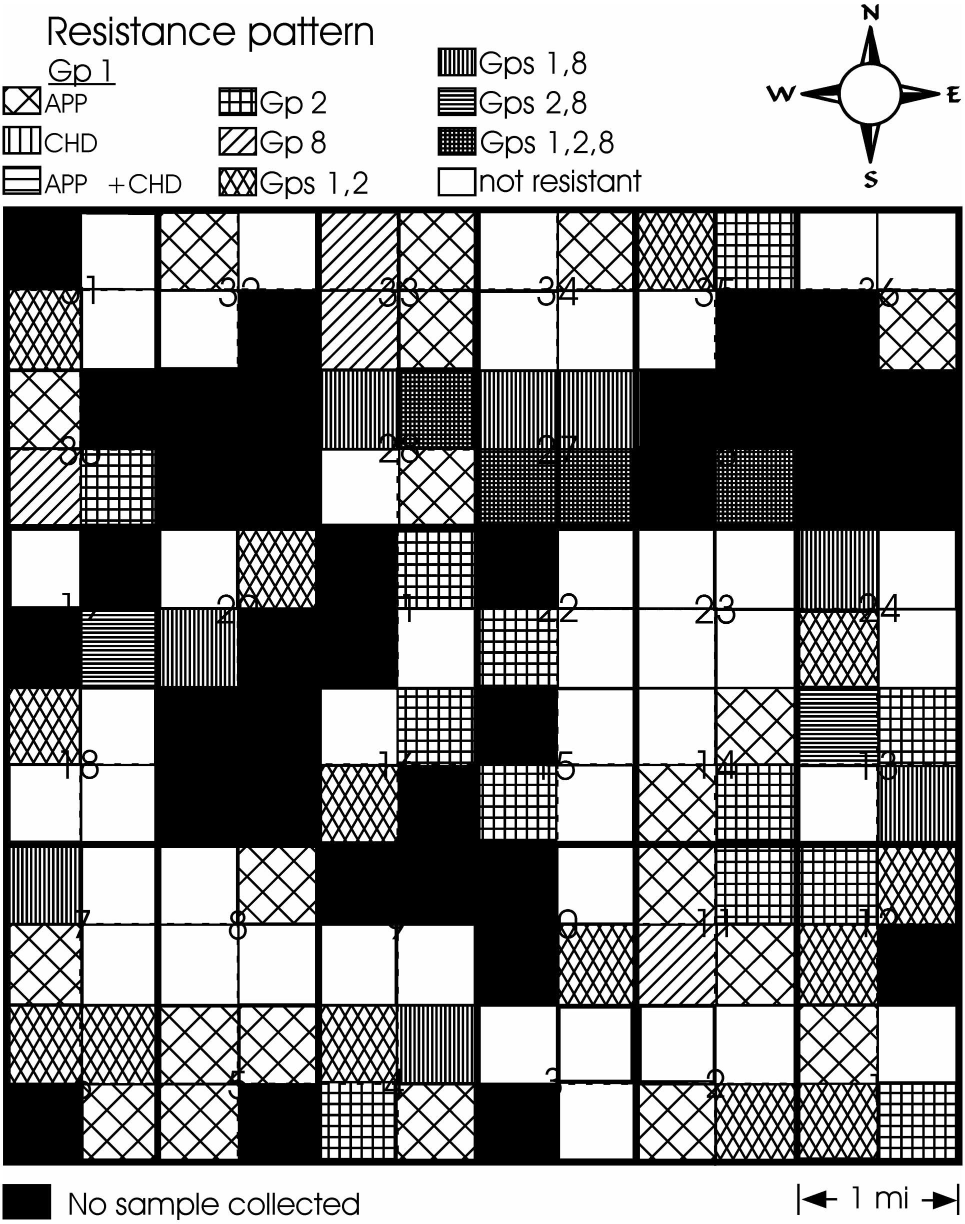


Figure 2. Patterns of resistance in wild oat in quarter-section fields (64 ha) in a township in Saskatchewan in 1997 (Source: Beckie et al. 2001).

Impact of herbicide-resistant crops on selection for resistant weeds

In Canada, six HR crop species - Argentine canola (*Brassica napus* L.), Polish canola (*Brassica rapa* L.), flax (*Linum usitatissimum* L.), corn, soybean, and wheat - are registered or soon will be registered (Table 3) (Anonymous 1994a, b, 1996, 1999a, b, c, 2000). HR crops can play a positive role in slowing the selection of HR weeds by increasing crop and herbicide rotational options. HR crops could increase profitability and the use of environmentally benign herbicides (Burnside 1992). Impact is largely dependent on the herbicide group and cropping area. Weeds resistant to Group 6 (benzonitriles), Group 9 (glyphosate) and Group 10 (glufosinate) herbicides are very rare (Heap 2000a). Increasing the use of these products will slow the selection of weed resistance to herbicides of other modes of action, including Groups 1, 2 and 5 (triazines). Frequent use of herbicides from Group 6, 9, or 10 would, however, increase the selection for very rare resistance genes. The existence of glyphosate-HR weed biotypes of three species suggests that other weeds may also be selected for resistance. Given the importance of glyphosate in reduced tillage cropping, repeated glyphosate use should be dissuaded. The use of Group 2 herbicides in imidazolinone-HR crops will maintain or increase the selection for Group 2-HR broadleaf weeds and increase selection for Group 2-HR grass weeds.

Impact of resistant crops as weeds

Volunteer crops are common weeds and weediness depends upon species, management practices, seed shatter prior to harvest and disbursement of seed at harvest (Table 4). Chemical control options are generally more limited if volunteers are HR. Measured after herbicide application, volunteer canola (*B. rapa* or *B. napus*) occurred in 8, 13, and 11% of fields in Alberta (Thomas et al. 1998a), Saskatchewan (Thomas et al. 1996), and Manitoba (Thomas et al. 1998b), respectively. Densities in direct-seeded fields in Manitoba were double that in conventional-tillage fields (Thomas et al. 1994). Volunteer *B. rapa* can exist for up to 15 years in the seedbank, compared to 3 to 4 years for *B. napus* (P. Thomas, personal communication). Glyphosate-HR *B. napus* remains uncontrolled where glyphosate is used alone for pre-seeding or chem-fallow weed control. Similarly, imidazolinone-HR *B. napus* is uncontrolled in crops that receive only Group 2 herbicides. However, all volunteer *B. napus* can be controlled by alternative herbicides including several inexpensive auxinic herbicides, such as 2,4-D and MCPA, or by using herbicide mixtures or non-chemical weed control strategies.

Table 3. Herbicide-resistant crops and resistance traits currently registered or being reviewed.

Species	Herbicide resistance	Variety registration	Food safety approval
B. napus	Glyphosate	Yes	Yes
	Glufosinate	Yes	Yes
	Imidazolinone	Yes	Yes
	Bromoxynil	Yes	Yes
B. rapa	Glyphosate	Yes	Yes
	Glufosinate	Yes	Yes
Z. mays	Imidazolinone	NA[a]	Yes
	Glufosinate	NA	Yes
	Sethoxydim	NA	Yes
	Glyphosate	NA	Yes
L. usitatissimum	Sulfonylurea	Yes	Yes
G. max	Glyphosate	Yes	Yes
	Glufosinate	No	No
T. aestivum	Imidazolinone	Yes	Yes

[a] NA, not required.

Volunteer wheat is a significant weed in 8, 9, and 10% of fields in Alberta (Thomas et al. 1998a), Saskatchewan (Thomas et al. 1996), and Manitoba (Thomas et al. 1998b), respectively, and can persist for at least 5 years in the seedbank (A. G. Thomas, unpublished data). Volunteer wheat is controlled by glyphosate, applied pre-seeding or in glyphosate-HR canola crops. Alternatively it can be controlled by Group 1 herbicides in canola or other broadleaf crops or by glufosinate in canola. It is poorly controlled in barley (*Hordeum vulgare* L.). Thus, imidazolinone-HR wheat is unlikely to be more difficult to control than conventional cultivars. Should glyphosate-HR wheat become registered, its control will be limited both pre-seeding and in-crop. We can predict that Group 1 product use might increase for control of glyphosate-HR volunteers.

If crops are partial or obligate outcrossers (allogamous) and grown in close proximity to conventional crops, HR genes may be transferred to conventional parental plants and hybrid seed formed. Growers can experience unanticipated HR volunteers. The movement or 'escape' of HR genes impacts the general public's perception of biotechnology safety. Species with outcrossing potential include canola (*B. rapa*, *B. napus*) and corn (Table 4). Gene movement in *B. rapa* has not been reported in Canada, but contamination of *B. napus* seed has been widely and sensationally reported.

Table 4. Herbicide-resistant crops grown in Canada, weediness, and traits likely to influence the occurrence of multiple-resistant volunteers and introgression of herbicide resistance traits.

Species	Breeding system	Weediness			Weedy relatives
		Crops	Disturbed areas	Natural areas	
B. rapa	Obligate outcrosser	Yes	Yes	No	Yes
B. napus	20-30% outcrosser	Yes	No	No	Yes
G. max	Highly autogamous	Rarely	No	No	No
L. usitatissimum	Highly autogamous	Yes	No	No	No
T. aestivum	Highly autogamous	Yes	No	No	Yes
Z. mays	Both self and cross-pollinated	Yes	No	No	No

If more than one HR trait has been developed for a species and the species is partially or completely allogamous, pollen flow could create multiple-HR volunteers. Multiple-HR volunteers have been reported in *B. napus* (Champolivier et al. 1999; Hall et al. 2000; Simpson et al. 1999). In 1997, a field in Alberta was planted with both imidazolinone-HR and glufosinate-HR *B. napus*, adjacent to a field of glyphosate-HR *B. napus*, (Figure 3). Volunteers were selected with glyphosate in 1998. These volunteers flowered and produced seed. Seed contained individuals resistant to glyphosate and glufosinate; glyphosate and imazethapyr; and glyphosate, imazethapyr, and glufosinate.

Under field conditions, pollen flow from one field to another generally results in less than 1% outcrossing in the first 100 m (Downey 1999). However, assuming a 0.2% outcrossing rate in a field yielding 1400 kg ha^{-1} with a harvest loss of 5%, Downey (1999) estimated some 35,000 hybrid seeds (3.5 seeds m^{-2})

would remain in the recipient field although most would be killed by spring frost or cultivation. Because of the large acreage of HR canola in western Canada, it is predicted that many fields contain multiple-HR volunteers.

In the absence of herbicide selection, it is unlikely HR crops are more competitive than conventional crops species, suggesting they will not invade disturbed or natural areas (Warwick et al. 1999). *B. napus* is not considered as a noxious weed, nor is it reported as a pest in managed ecosystems or being invasive in natural ecosystems (Anonymous 1999c).

Where herbicides are used in non-crop disturbed areas, the potential invasiveness of HR crops may be greater. For example, the use of glyphosate or Group 2 herbicides at oilwell sites or along roadsides adjacent to cropland might result in a lack of control of HR crop volunteers. However, because natural vegetation is rarely selected by herbicides, it is unlikely that HR traits will increase invasiveness of crops into unmanaged (natural) areas.

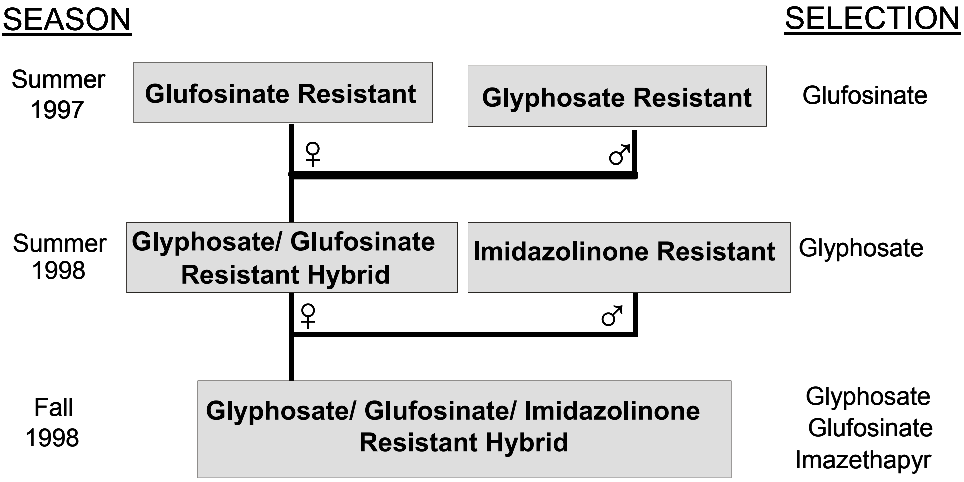


Figure 3. Proposed cross-fertilization events and selection pressure leading to the presence of glyphosate-, imidazolinone-, and glufosinate-resistant canola (*B. napus*) volunteers located at a site in Alberta in 1997 (Source: Hall et al. 2000).

Introgression of herbicide resistant genes in weedy relatives

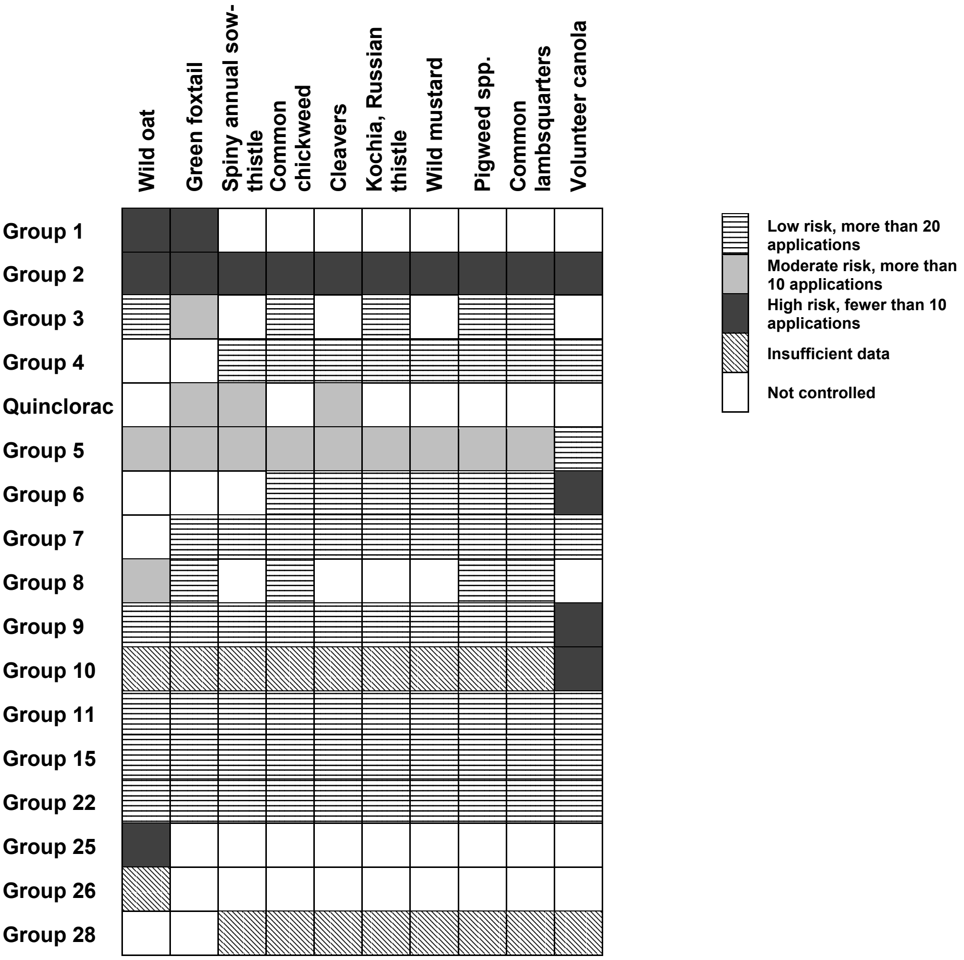
Introgression, the stable incorporation of genes from one differentiated gene pool into another, can only occur if barriers of incompatibility, genetic instability and low hybrid pollen fertility are overcome. It is also influenced by crop acreage grown and the frequency of weedy relatives in or adjacent to cropping areas (Table 4). Introgression of HR traits from *B. napus* into genomes of wild mustard (Bing et al. 1996; Lefol et al. 1996) appears to be unlikely. However crosses between *B. napus* and wild radish (*Raphanus raphanistrum* L.) (Chèvre et al. 1998, 2000; Darmency et al. 1998) and dog mustard [*Erucastrum gallicum* (Willd.) O. E. Schulz] (Lefol et al. 1997) have produced F1 hybrids. *B. napus* and wild radish hybrids were vigorous but mostly sterile, whereas *B. napus* and dog mustard hybrids were not vigorous but produced fertile progeny that resembled dog mustard when backcrossed to the dog mustard parent. The transfer of HR traits from *B. napus* to weeds in agro-ecosystems has not been demonstrated. In a single incidence, Chèvre et al. (2000) reported the transfer of the HR trait from *B. napus* to wild radish. A single hybrid was identified from among the 189,084 wild radish seeds screened.

Introgression of traits from wheat is primarily limited by the autogamous nature of the species. There are no wild *Triticum* species in Canada. However, several species in the genus are grown as naturalized and cultivated plants and form hybrids with wheat. They are used as specialized crops, forage crops, or for reclamation purposes. They include triticale (X *Triticosecale* Wittmack), Dahurian wild rye (*Elymus dahuricus* Turcz. ex Grieseb.), Russian wild rye (*Elymus junceus* Fisch.), Sea lyme grass, strand-wheat –naturalized [*Leymus arenarius* (L.) Hochst], Sea lyme grass, strand-wheat –native (*Leymus mollis* Trin), intermediate wheatgrass [*Agropyron intermedium* (Host) Beauv.], tall wheatgrass [*Agropyron elongatum* (Host) Beauv.], and crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.]. Quackgrass [*Elytrigia repens* (L.) Nevski] is a widespread weed in cropping areas of Canada. While it is possible for hybrids to be formed between wheat and *Agropyron* spp., naturally-occurring hybrids have not been reported (Knott 1960). Introgression of HR genes from wheat has been shown to be possible with jointed goatgrass (*Aegilops cylindrica* Host) (Seefeldt et al. 1998). Occurrence of this weed has not been reported in Canada, although populations in Washington State and Idaho are close to the Canada-U. S. border (Anonymous 1999a).

Outlook for delaying or managing herbicide resistance

Around the world, growers have been reluctant to proactively manage weeds to delay the selection for herbicide resistance. If the cost and effort of prevention is the same as that of the cure, growers are reluctant to change their weed management program until after resistance has occurred. Occam's paraphrased philosophy of KISS – 'keep it simple, stupid' has to be thrown out and replaced with Gressel's philosophy of KISS - 'keep it sophisticated, smarty' (Gressel 1997). Selection pressure has the greatest impact on resistance development and is a factor that growers can reduce or vary by the use of herbicide rotations, mixtures, and application timing (pre-seeding, in-crop, pre- and post-harvest). Encouragingly, growers are increasingly practicing herbicide group rotation as a cornerstone of resistance management (Beckie et al. 1999a; Bourgeois et al. 1997b; Goodwin 1994). Herbicide rotations, mixtures, or sequences generally have the greatest effect in delaying resistance when the mechanism conferring resistance is target site-based, target weed species are highly self-pollinated, and seed spread is restricted. For example, there is little ALS inhibitor resistance in fields in Europe or Japan where Group 2 herbicides are used in rotation or mixture with other herbicides (Heap 2000a, Itoh et al. 1999). Growers who included mixtures of herbicides with different modes of action coupled with crop rotation, tillage, and various cultural practices were less likely to select HR weed populations (Shaner et al. 1997). If mixing partners do not meet the criteria of similar persistence and efficacy but different propensity for selecting for resistance in target species, the effectiveness of mixtures for delaying resistance will be reduced and may inadvertently accelerate evolution of multiple resistance (Sprague et al. 1997). Metabolism-based resistance conferring resistance to herbicides of different modes of action will clearly limit the effectiveness of herbicide group rotation as a tool to delay resistance. Testing suspected populations to determine resistance patterns will identify remaining herbicide options for growers (Beckie et al. 2000). Guidelines for rotating herbicides with different propensity to be metabolized need to be developed to combat increasing cases of metabolism-based HR grass weed populations.

Not all herbicides have the same probability of selecting for resistance in weeds (Figure 4). The 'one in three' rule advocated in the 1990s pertained to all herbicides, regardless of mode of action. Although it was a good rule of thumb for herbicide group rotation, it was based on anecdotal evidence for time of evolution of Group 1 resistance in wild oat. Growers need more sophisticated information now. Simply stated, the higher the risk of a herbicide mode of action of selecting for resistance, the less often herbicides from that group should be applied. It is widely agreed that Group 1 and 2 herbicides pose a high risk for selecting HR biotypes relative to herbicides from other groups (Dellow et al. 1997; Gressel 1997; Heap 1999; LeBaron and McFarland 1990). Lower risk, non-selective herbicides, such as Group 22 (paraquat/diquat) or Group 9 (glyphosate) should be used pre-seeding to reduce the number of weeds selected with higher risk, in-crop herbicides. It may be necessary to delay seeding to take advantage of non-selective herbicides or tillage prior to seeding. Pre-harvest applications of Group 9, 10, or 22 herbicides should be investigated further to determine the relative loss of weed seed viability (Bennett and Shaw 2000).



	Wild oat	Green foxtail	Spiny annual sow-thistle	Common chickweed	Cleavers	Kochia, Russian thistle	Wild mustard	Pigweed spp.	Common lambsquarters	Volunteer canola
Group 1	■	■	□	□	□	□	□	□	□	□
Group 2	■	■	■	■	■	■	■	■	■	■
Group 3	▤	▒	□	▤	□	▤	□	▤	▤	□
Group 4	□	□	▤	▤	▤	▤	▤	▤	▤	▤
Quinclorac	□	▒	▒	□	▒	□	□	□	□	□
Group 5	▒	▒	▒	▒	▒	▒	▒	▒	▒	▤
Group 6	□	□	□	▤	▤	▤	▤	▤	▤	■
Group 7	□	▤	▤	▤	▤	▤	▤	▤	▤	▤
Group 8	▒	▤	□	▤	□	□	□	▤	▤	□
Group 9	▤	▤	▤	▤	▤	▤	▤	▤	▤	■
Group 10	▧	▧	▧	▧	▧	▧	▧	▧	▧	■
Group 11	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
Group 15	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
Group 22	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤
Group 25	■	□	□	□	□	□	□	□	□	□
Group 26	▧	□	□	□	□	□	□	□	□	□
Group 28	□	□	▧	▧	▧	▧	▧	▧	▧	▧

▤ **Low risk, more than 20 applications**
▒ **Moderate risk, more than 10 applications**
■ **High risk, fewer than 10 applications**
▧ **Insufficient data**
□ **Not controlled**

Figure 4. Classification of herbicide mode of action by risk (high, moderate, and low) for selection for resistance in specific weed species in Canada.

More sophisticated information provided to growers to tailor label rates according to environment conditions and herbicide sensitivity of the species present in their fields is required. For example, reduced but effective ALS inhibitor herbicide rates used to control common chickweed in Europe compared to those used in western Canada doubled the time for resistance evolution by reducing the time that herbicides remain active in the soil (Kudsk et al. 1995).

With the exception of frequency of fallow in the rotation (which was inversely related to frequency of herbicide-group use), resistance development in wild oat was little affected by cultural practices used by growers (Légère et al. 2000). Although consistency and efficacy of cultural practices pale in comparison to herbicide performance, synergies can be realized which provide opportunities to reduce herbicide inputs (Kirkland and Beckie 1998). By consistently doing the ‘small things’, such as planting weed-free crop seed, increasing seeding rates of cereals, banding fertilizer, and diversifying crop rotations, growers will have the best chance to reduce herbicide inputs and consequently, the selection pressure for resistance evolution. Using non-chemical weed management options will not affect the selection pressure *per se*, however, if herbicide-use patterns in a field remain the same.

To manage resistance, growers first use alternative herbicides. With the cost of discovering, developing, and marketing a novel herbicide at approximately $100 million U. S. in 2000 (Dunan and Westra 2000), growers should not expect many compounds with novel modes of action to be commercialized in the next few years. Expansion of crops resistant to existing herbicides (e.g., glyphosate) will continue to influence future herbicide-use patterns. Although containment of HR patches at early stages of development by herbicides or non-chemical methods is recommended and research has shown it to be effective (H. J. Beckie, unpublished data), most growers fail to detect small HR patches (Beckie et al. 1999c). Field scouting after in-crop herbicide application is not convenient because of the large size of most farms. If the HR population covers a wide area across the field, management should focus on reducing seed return by using lower risk herbicides in conjunction with cultural practices, such as silaging (Harker and Kirkland 2000), growing competitive annual crops or perennial crops, or collecting weed seeds at the time of harvest. Considerations other than resistance management, however, influence the degree of utilization of these practices by growers.

The cost of resistance is minimal if cost-effective alternatives are available (e.g., auxinic and photosystem I resistance). However, prevention can cost significantly less than dealing with resistance once it fully develops, where multiple herbicide resistance occurs, or where few alternative herbicides are available. Most or all alternative herbicides to control multiple-group HR biotypes of wild oat or green foxtail increase costs to growers (Beckie et al. 1999b, c). The very limited number of alternative herbicide modes of action to control some multiple-group HR biotypes is equally as important as the cost.

Multiple-group resistance has been the chief impetus for the adoption of integrated weed management (IWM) strategies (Powles et al. 1997, 2000). Based on past global experience, growers only embrace IWM strategies after the development of resistance, thus managing resistance retroactively not proactively. In Canada, the increasing size of farms with concomitant limited labor and time availability have reinforced our heavy reliance on herbicides as the predominant weed control tool. Nevertheless, there is reason for optimism in future grower adoption of IWM strategies. A remarkable paradigm shift with respect to management of multiple-group resistance in annual ryegrass was observed by Powles (1997): "It is the experience of some researchers, advisers and growers that the changes to farming systems (IWM) which have been forced by the appearance of multiple herbicide resistance have resulted in more sustainable and even more profitable farming systems than prevailed before resistance developed!".

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Developing integrated weed management systems

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In recent times, weed control practices for major crops have been dominated by the use of selective herbicides. The impact of herbicides is such that weed science is often perceived to be the science of herbicides rather than the science of weeds. While herbicides and other control practices are important, equal attention should be given to understanding the nature of weed communities and the factors that shape them. Greater consideration of these factors is necessary if we are to develop more integrated weed management systems. Changes in weed management can be attained within the framework of existing cropping systems. However, given the lack of options, a major effort to develop new methods and approaches to weed management is needed. Weed scientists need to play a central role in the development of new cropping systems to make weed management an integral component of the system. While it is hoped that expanding our knowledge of weed community dynamics will lead to new methods for weed management, this knowledge will also be needed to preserve the effectiveness of the tools we currently possess.

Introduction

Weeds have a significant economic impact on agricultural production. In the United States alone, it was estimated weeds and weed control have an annual economic impact of more than $15 billion (Bridges 1994) with even greater relative costs in developing countries (Akobundu 1991). Concerns over the economic costs and environmental impacts of current practices (Flora 1995; National Research Council 1989; Radosevich and Ghersa 1992) have lead many weed scientists and crop producers to seek alternative strategies for weed control (Gressel 1992; Wyse 1992). Herbicides are important tools for modern agriculture, but have become too dominant in many production systems. New control options and management knowledge will give producers more flexibility and help preserve the effectiveness of herbicides. Using herbicides in a more integrative manner will help forestall the development of weed resistance and reduce the potential for environmental contamination.

Herbicides have been valuable tools and have provided benefits to the farm and urban communities. However, weed management should be viewed as an integrated science (Burnside 1993). Increased attention must be given to biological, cultural, mechanical, and preventive tools and techniques to manage weeds. Refocusing away from dependence on a single technology (herbicides) in a simplified cropping system will require a greater understanding of biological systems than we currently possess (Holt 1994; Navas 1991).

Weed management

Weed management implies a shift away from reliance on control of existing weed problems and places greater emphasis on prevention of propagule production, reduction of weed emergence in a crop, and minimizing weed competition with the crop (Buhler et al. 2000; Zimdahl 1991). Weed management emphasizes integration of techniques to anticipate and manage problems rather than reacting to them after they are present. The goal is to maximize crop production where appropriate and optimize grower profit by integrating preventive techniques, scientific knowledge, management skills, and the best control techniques. While additional knowledge is needed in all areas of weed management, the most important task of weed science is to increase knowledge of weed biology and ecology, creating a better understanding of weediness. This knowledge will lead to the use of appropriate management techniques that will not only produce short-term results, but also develop long-term solutions to persistent weed problems.

Weed control science and principles of weed population dynamics

It was proposed that weed science research can be separated into two major categories; weed control science and technology and principles of weed population dynamics (Buhler 1996; Wyse 1992). If we are to view weed management as an integrative science, we must also include a category for integrating the science and technology generated into new management systems. Research on weed control science and technology involves herbicides, tillage, biological control, and other methods to remove unwanted vegetation from a disturbed system (Table 1). Research on principles of weed population dynamics focuses on weed biology and ecology, examining why weeds are present and their impacts on the production system.

Principles of weed population dynamics provide an understanding for the basis of weed problems. This research is the basis for new, ecologically based, weed management systems. The knowledge gained will provide the foundation for development of new strategies and more efficient techniques, resulting in more reliable weed management systems that are cost effective and pose less threat to the environment. Such research is also consistent with the principles of integrated pest management which center on knowledge of pest biology and ecology (Smith 1978). Weed science has lagged behind other pest management disciplines in developing integrated management systems, largely due to our limited understanding of the principles of weed population dynamics (Burnside 1993).

Table 1. Examples of weed science research categorized as 1) weed control science and technology and 2) principles of weed population dynamics (modified from Wyse 1992).

Control science and technology	Principles of weed population dynamics
* Herbicide development	* Seed and bud dormancy mechanisms
* Biological control	* Seed development and production
* Allelopathic cover crops	* Population genetics
* Tillage	* Seedbanks and emergence dynamics
* Herbicide selection decision aids	* Weed/crop interactions
* Managed competition	* Population shifts
* Competitive cultivars	* Modeling weed/crop systems
	* Spatial distributions

The term “integrated pest management” or IPM first appeared in the literature in 1967 (Smith and van den Bosch 1967) and has its root in the concept of integrated control (Stern et al. 1959). While many definitions of IPM have been proposed, they all contain two key elements: (1) the use of multiple control tactics and (2) the integration of knowledge of pest biology into the management system (Bottrell 1979). As such, developing integrated management strategies for weeds calls for broader approaches that move beyond control of existing weed populations (Liebman and Gallandt 1997). For example, integrating cropping system design and weed science could lead to systems that best utilize resources, diversify the selection pressure on weed communities, and provide producers a broader range of management options.

The progression from a focus on tools targeted at a single weed population at a given time to the adoption of a holistic approach to crop and weed management will require analysis, theory, and information to support implementation at the cropping system and ecosystem levels (Cardina et al. 1999). Integrated weed management must be developed within the context of the entire cropping system with the farm and the surrounding area being considered as part of a larger ecosystem. A better understanding of the factors that affect ecosystem health, population dynamics of the weeds, and weed and ecosystem response to management practices is needed (Liebman and Gallandt 1997). We need to integrate cropping systems and integrated pest management concepts to include comprehensive theories that include all management variables, building on the foundations provided by the theories and practices of plant ecology, population management, plant protection, and cropping systems.

Approaches to developing integrated weed management systems

Significant new challenges are developing for individuals involved in managing weeds in agronomic crops. Environmental regulations, reduced tillage systems, increasing farm size, economic pressure, and industry consolidation and product cancellations are restricting the weed control options available to crop producers. In addition, weed populations continue to adapt to production practices through herbicide resistance and population shifts. Limited crop choices are reducing crop rotation and intensifying the selection pressure on weed communities.

Fundamental changes in weed management will not occur instantaneously. We need both short- and long-term approaches to developing integrated weed management systems. Short-term approaches will apply existing knowledge, provide immediate benefits, and provide transition to new systems (Table 2). Long-term approaches may require basic changes in crop management systems and must provide unique methods to manage weeds.

Short-term approaches

Short-term approaches to more integrated weed management centers around reducing herbicide use and maintaining weed control in current cropping systems. Many methods may be used to reduce herbicide use (Table 2). However, the ability to reduce herbicide use varies among growers. Growers with good management skills and fields with low weed pressure can reduce herbicide use and incur only a slight risk of weed control failure. For others, the savings achieved by reducing herbicide use may be small compared with the risk of control failures, crop yield losses, the additional time needed for weed control, and increased weed densities in future years.

Mechanical weed control to supplement or replace herbicides remains an option in many cropping systems (Gunsolus 1990). Properly designed and executed mechanical control systems are effective on most weed species. The increased use of reduced tillage systems has lessened the applicability and effectiveness of some mechanical control operations (Springman et al. 1989). However, interrow cultivation is an integral component of ridge-tillage (Forcella and Lindstrom 1988) and has been effective in combination with reduced rates of herbicides in corn planted into untilled seed beds (Buhler et al. 1995).

Table 2. Potential approaches for short- and long-term development of integrated weed management strategies.

Short-term tactics	Long-term tactics
Application of existing knowledge	Weed biology and ecology
- scouting	- population biology
- increased management	- weed/crop interactions
Refinements of current systems	- emergence and growth predictors
- combining control tactics	Site-specific management
- treatment thresholds	- herbicide application
- appropriate use of tillage	- soil and crop management
- decision aids	Redesign cropping systems
- reduced rates of herbicides	- increase rotation and diversity
- application technology	- improve resource utilization
	- new tillage systems
	New control methods
	- biological control
	- allelopathy
	- managed competition
	- competitive cultivars

Banding of herbicide over the crop row and using cultivation to control weeds between the rows is a proven method to reduce herbicide use (Hartzler 1993). Banding is an excellent tool for reducing herbicide use for growers who already practice interrow cultivation. Applying herbicides at rates below those listed on product labels is another method to reduce total use. While legal, growers using reduced rates assume responsibility for herbicide efficacy.

Scouting fields and maintaining accurate field records are critical components of efficient weed management programs (Hartzler 1993). Maintaining records for several years allow for assessment of weed populations and distribution patterns within fields. Fields where excellent control has been maintained for several years should have low weed densities and provide opportunities for reducing herbicide use. Emerging technologies such as global positioning systems (GPS) and geographic information systems (GIS) may improve weed mapping, record keeping, and scouting (Mortensen et al. 1993).

Weed thresholds (O'Donovan 1996) and associated models (Swinton and King 1994; Wiles et al. 1996) may provide a mechanism to improve weed control decisions. Threshold models are based on an assessment of weed pressure and the relationship of this pressure to immediate and future yield losses and costs of control. Economic thresholds are being used in insect and disease management and should find greater application in weed management as existing knowledge is applied and new knowledge is developed (O'Donovan 1996).

Long-term approaches

Long-term approaches to integrating weed management (Table 2) are more difficult to define than short-term herbicide use reduction. Currently, weed control practices are justified by the knowledge that weed populations are very difficult to eliminate once established, uncontrolled plants contribute to future infestations, and cause direct economic losses when left uncontrolled. None the less, we seldom examine the causes of the perpetual presence of weeds. Herbicides are often used as a solution to problems they helped create. Attempts to solve a problem with the same technology that generated the problem usually result in a similar, but more difficult problem (Ferre 1988). For example, addressing herbicide resistance by using different herbicides, may create multiple- and cross-resistance, eventually destroying the control efficacy of each chemical on that pest (LeBaron and Gressel 1982).

A more integrative approach to weed management might consider that weed populations have specific environmental niches that mimic the crops grown or take advantage of the conditions created in establishing the crop. For example, summer annual weed species predominate in a corn/soybean rotation because both crops are summer annuals. In addition, growing crops in rows provides space and light for weeds. Cropping systems that discourage build up of adapted weed species and biotypes must be as diverse and resource efficient as possible. Diversity may be attained by including crops with differing life cycles, differing tillage intensity and timing, and using all available control methods. Resource use may be improved by changing planting dates and patterns, using crop cultivars with rapid early growth, and planting cover crops. A new perspective might also consider that a diverse, low density weed population may have a positive role in the agroecosystem (Odum and Biever 1984).

New methods of weed control may also play an important role in the development of integrated weed management systems. While private industry may continue to provide new chemical technology, biologically-based control tactics are needed to facilitate integrated weed management systems. Currently, weed science has few, if any, alternatives to tillage and herbicides that are economically and environmentally desirable.

Research has developed technologies that may provide new methods for weed control (Table 2). Biological control is an established practice in some systems, but has had minimal impact on weed management in agronomic crops (Gressel 1992). Most instances where biological control of weeds has been successful are where there is a single target weed in a stable environment, such as pasture or rangeland (Strobel 1991). Biological control of weeds in annual cropping systems is complicated by the instability of the environment, multi-species weed complexes, and the desire for near complete control. Innovative approaches, such as microorganisms that attack the seeds or seedlings in the soil (Kremer 1993; Harris and Stahlman 1996), may provide new biological control options. Other biologically-based control tactics, such as allelopathic crops or crop residues (Duke 1990), smother plants (DeHaan et al. 1994), and crop cultivars with enhanced competitiveness with weeds (Pester et al. 1999) also offer potential as components of integrated weed management systems.

Conclusions

The basis of weed science has been control technology rather than understanding weedy species and their roles in the agroecosystem. Weeds have been present since the beginnings of organized agriculture and are not likely to disappear in the near future. All forms of disturbance result in survival and selection of the best adapted weeds (Holt 1994). Any cropping system that exerts a continuous, strong selection pressure will cause a build-up of the best adapted weed species and biotypes. Development of integrated weed management systems will require an approach that considers the processes and patterns that link fundamental scientific, economic, and sociological disciplines to agricultural systems.

The scientific disciplines of weed science and production agriculture must change by taking a broader view of weeds as part of the crop ecosystem and by addressing the long-term questions surrounding weed perpetuation, crop production practices, and weed control technology. Agricultural systems are composed of interacting production, environmental, biological, economic, and social components. These interactions require the study of not only the parts, but also the entire system (Holling 1978). Long-term improvements in weed management and agricultural production systems, will require a convergence of traditional agriculture, ecological theory, economics, and sociology (Levins 1986; Radosevich and Ghersa 1992). Linkages among these disciplines will form the basis for successful, stable, and profitable cropping systems.

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Integrated weed management – making it work

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Integrated weed management (IWM) is a system that involves a continuum of inter-dependent cultural, biological and herbicidal weed control practices. It is essential that IWM involves an array of tools including the rotation of available herbicide Groups, ensuring that weeds are exposed to a diverse range of control mechanisms. The aim of IWM is to reduce selection for resistance to any single control agent and to manage herbicide resistant weeds within a profitable system. Since effective herbicides offer such a good cost-benefit ratio, producers and agronomists are often loath to fully implement IWM, because it will reduce short-term income. There are currently two major approaches to IWM extension in southern Australia. Meetings, seminars and workshops have been used to educate producers and agronomists about resistance and the need for IWM. In addition, a significant effort has been put into the establishment of on-farm IWM demonstrations. The demonstrations involve whole fields or at least large plots that can be managed using producer's equipment and these have proven to be highly effective as learning tools as well as generating data on weed seedbanks. IWM extension in Australia has been greatly enhanced by the existence of the Cooperative Research Centre for Weed Management Systems (CRC). The CRC has fostered interstate and agency cooperation and networking and it has accelerated progress by approximately three years.

Introduction

Australia produces a wide range of crops including sugar cane, cotton, rice, grapes, apples, maize and many others, highlighting the diversity of climates and soil types. While herbicide resistance impacts on all crops, this paper deals only with winter growing crops through the southern wheat belt. The majority of the winter growing crops are grown under rain-fed or dryland conditions, relying on incident rainfall and stored soil moisture. In 1999, Australian producers grew 15 million ha of cereals, 1.9 million ha of pulse crops, and 1.5 million ha of canola (50% of which were triazine tolerant cultivars).

Herbicide resistance now affects 22 weed species in Australia (Preston et al. 1999). Some important examples include wild oat (*Avena fatua* L, and *A.*

ludoviciana Durieu), wild radish (*Raphanus raphanistrum* L.), and Indian hedge mustard (*Sisymbrium orientale* (L) Scop.). By far the most problematic species is annual ryegrass (*Lolium rigidum* Gaudin) which has developed resistance to six mode of action Groups, with over 1000 fields resistant to Group 1 herbicides and over 1000 fields resistant to Group 2 herbicides (Preston et al. 1999).

Of all the States, the Western Australian (WA) situation is worst. Many WA producers developed simple crop sequences containing only lupin (*Lupinus* spp.) and wheat. The two crops were grown in continuous wheat-lupin-wheat-lupin rotation, relying on a limited range of herbicides from Groups 1 and 2. Consequently, resistance is common and severe through the cropping belt of WA.

Resistance in WA has forced major changes on producers. For example, one producer northeast of Perth who has a 6000 ha operation has only one selective herbicide (clethodim) left to use against annual ryegrass. This producer has been forced into a situation where one third (2000 ha) of the available area has to be taken out of crop production and put into pasture, so that weed numbers can be reduced and the useful life of clethodim is maximized. Because of low livestock product prices and the high cost of weed control practices, income from the pasture is low or negative. As a result, resistance has imposed a significant toll on the operation.

Integrated weed management (IWM)

IWM is a system that involves a continuum of inter-dependent cultural, biological and herbicidal weed control practices. It is essential that IWM involves an array of tools including the rotation of available herbicide Groups, ensuring that weeds are exposed to a diverse range of control mechanisms. The aim of IWM is to reduce selection for resistance to any single control agent and to manage herbicide resistant weeds within a profitable system.

Producers and agronomists in every southern State of Australia are well aware of resistance. Many could answer in-depth questions about resistance and explain the meaning of IWM. Even though producers seem to be willing to adopt some components of IWM (such as increased seeding rates), few are willing to become strongly pro-active in regard to the problem. There is a range of legitimate reasons for this attitude:

1. Effective herbicides offer the most cost-effective, minimal planning requirement solution to weeds.
2. Non-selective weed management options add directly to costs and producers tend to evaluate options on an annual, short-term basis, rather than on a whole rotation, long-term basis.

3. IWM systems may involve options (eg livestock, cultivation or crop residue burning) that the producers have difficulty using or that they simply wish to avoid. In some cases, other issues have higher priority.
4. IWM systems, to be effective, require more monitoring, record keeping and forward planning than the simplistic herbicide approach.
5. IWM requires an opposite approach to the "old" threshold level notion where treatment was indicated once weeds exceed a certain threshold in any season. IWM aims at maintaining low weed densities on a rotation long basis so that when herbicides are used, small weed populations are treated.

Even with the promise of fewer resistance problems, there is an Australia wide reluctance to fully adopt IWM while effective herbicide options exist. This attitude is exemplified in the cropping belt with wide adoption of trifluralin in response to the development Group 1 and 2 resistance.

Herbicide resistance has evolved at different rates in Australia. For example, Western Australia has had a severe and widespread problem for the last decade, while southern New South Wales (NSW) is encountering a similar problem and in northern NSW and southern Queensland (Q), the problem is just starting. These differing rates of development reflect the intensity of herbicide use in the different regions.

This situation can be explained because of the different cropping regimes that commonly apply. The cropping regimes are related primarily to seasonal conditions but also strongly influenced by soil types. For example, the wheat cropping belt of WA has a Mediterranean climate with little if any summer rainfall. Much of the area has light textured soils. At the other extreme, in northern NSW and southern Q, rainfall is increasingly summer dominant and the predominant cropping soils are heavy textured. As previously outlined, a common rotation in WA was to have a lupin-wheat-lupin program, no till, stubble retained, and with the constant use of Group 1 and Group 2 herbicides. In contrast, about 70% of southern NSW crops are produced on a ley system, with 3 to 5 years of pasture[*] followed by 3 to 5 years of crop. In this system, the ley pasture allows tremendous scope for non-selective weed control and it seems likely that this has slowed the build up of resistance. In addition, these producers attempt to include 3 to 4 crop species, allowing growers to rotate herbicide more easily.

Northern NSW and southern Q growers have the option of a system that not only reduces herbicide resistance problems but reduces herbicide use overall. Because of favourable soils and a significant summer rainfall pattern, these

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[*] Ley pastures are usually legume dominated. The most common species are the "sub" clovers (*Trifolium subterraneum* L.) and lucerne (*Medicago sativa* L.). In WA, serradella (*Ornithopus* spp.) is commonly used on the lighter textured soils.

producers have the option of rotating summer growing crops like sorghum and sunflowers with winter growing crops of wheat, barley and chick pea (*Cicer* spp.). In this system, winter fallow can be used to reduce numbers of winter weeds. Conversely, where summer weeds are an issue, summer fallow periods can be used to control them.

Even though some cases of resistance have developed under the northern cropping system (eg *Phalaris paradoxa* L. to Group 1*,* *Sonchus* spp. to Group 2), the problem is much less widespread than in southern areas. Of great concern however is the number of putative cases of glyphosate resistance in annual ryegrass in the last three years. Producers with this problem have been no-till cropping for around 20 years using only glyphosate in the fallow period.

Extension methods used in Southern Australia

As has been outlined, herbicide resistance is a problem with no easy extension solutions and which requires a national approach (although specific programs will vary between regions). The extension process in Australia has been significantly enhanced by the presence of the Cooperative Research Centre for Weed Management Systems (CRC). The CRC has fostered cooperation and information sharing across the whole cropping belt by allowing the establishment of information networks and by providing funds for projects and travel. CRC involvement has enhanced the development of new weed control strategies. A strong network now exists involving State agencies, Universities, consultants and industry agronomists. Strong links also exist with the Grains Research and Development Corporation (GRDC) which is not only a major supplier of research and development (R&D) funds, but distributes information to agronomists and producers via seminars and newsletters. GRDC is partly funded by the Federal Government and partly by producer levies. The herbicide industry is also represented through "Avcare" (the national association for crop protection and animal health). Avcare has been able to make major contributions to extension. An important example of their input has been the labelling of containers with the herbicide Group designation (A through to N). This has contributed to producers awareness of the "Group" nomenclature. Because of the severity of resistance in Western Australia, the "Western Australian Herbicide Resistance Initiative" (WAHRI) has been set up with the single focus of herbicide resistance research. WAHRI is linked with the CRC and has a range of research and extension programs in place.

In southern NSW, weed R&D has been boosted with the establishment of the weeds group located at the Wagga Wagga Agricultural Institute. The group has an extension specialist, greatly enhancing the information flow between research staff, extension staff, and farmers. In keeping with the philosophy of group extension, a consultative group comprising extension agronomists, consultants, and leading producers has been set up to allow direct input into research projects of the weeds group.

Throughout the cropping belt of Australia, agronomists and producers are given the opportunity to attend meetings, seminars and other information days. The GRDC sponsored farmer and adviser updates are held regularly. IWM courses are being offered at the University level for internal and external students.

Naturally, a wide range of literature is available on such things as herbicide mode of action Groups and IWM guidelines. The key messages being promoted are:

1. Rotate herbicide mode of action Groups.
2. Treat small weed populations when applying herbicides.

While meetings and literature are clearly essential in the extension program, a great deal of effort is being put into demonstration work, where producers and agronomists can be physically involved or at least be able to see the results of a variety of management programs.

On-farm IWM demonstrations

A system of on-farm demonstrations have been established through the southern Australian cropping belt. The demonstrations aim to change farmers planning horizon from the short-term herbicide solution to the long-term population management and density reduction. While the demonstrations vary in structure, they have several important things in common:

1. Initiation and management of the demonstrations involves local farmers, either as a specific or pre-existing group.
2. There is no set design for the demonstrations, which may be complex or simple.
3. They are conducted for as many seasons as is needed to show a clear success or failure of a program.
4. They are large scale, involving whole fields or plots large enough to be managed with farmer equipment.
5. They are not experiments but involve best-bet treatment comparisons where latest research results can be used when appropriate.
6. Forward plans are flexible, as they would be on a farm.
7. The weed seedbank is monitored over time, either directly through soil sampling, or indirectly by counting plants and estimating seed rain.
8. Economic comparisons of different programs are calculated.
9. Field tours are conducted regularly.

The fact that the IWM demonstrations are conducted over a number of seasons on the same site contrast sharply with normal herbicide experiments, which are one season only and tend to promote the herbicide only method.

There are two broad types of demonstration that fit the above criteria. The first is the Western Australian model, where the work is conducted on a single site. There are 12 sites in WA, most of which are coordinated by Agriculture WA staff. Currently, NSW Agriculture coordinates seven sites although this is expected to increase. The second is the South Australian (SA) model that involves a large number of farm surveys. In the WA model, a range of management systems are planned by the committee and implemented on a single site. The SA farm survey model asks a large number of producers to choose two or three differently managed fields to monitor over time.

The IWM demonstration model

There are three examples of this model which illustrate the range of design possibilities, the York site in WA and the Young and Wallacetown sites in NSW.

York

This is one of several GRDC-funded IWM sites supervised by Mr. Bill Roy. Bill is a private research consultant and has been instrumental in developing this demonstration technique. A committee, including producers, planned the demonstration and work together to modify treatments when necessary. The key objective of the demonstration was to determine which series of weed treatments provide both reduced ryegrass seedbanks and provide optimum income over time.

At the time of establishment in 1996, this site had a wheat crop infested with 884 ryegrass plants m^{-2}. The ryegrass is resistant to diclofop, haloxyfop-R, sethoxydim, clethodim, and triasulfuron.

The demonstration area was divided into three initial treatment strips of about 0.8 ha each. The strips, orientated east-west, were about 400 m long and about 20 m wide. The spring 1996 crop treatments and subsequent 1997 ryegrass densities are shown in Table 1.

In 1997, the three strips were subdivided north-south into five sections (A to E), giving a total of 15 - 40 x 40 m blocks (1A to 3E) on which to test an array of management options. For brevity, management of blocks 1A and 2D is tracked from 1997 to 2000. Ryegrass densities are shown as cumulative figures, being the sum of three emergence counts through the season.

These data describe a dramatic contrast between two management programs. In Block 1A (Table 2), income was superior early in the program and deteriorated with time. The weeds did not cause the poor crop performances in 1998 and 1999. However, poor crop growth has allowed weed numbers to escalate. In Block 2D (Table 3), a short-term income reduction has been compensated for with rapidly improving economics and, significantly, a declining trend in weed numbers. The notion of accepting a short-term reduction in income to achieve a decreasing weed density is a core philosophy in IWM.

Table 1. Impact of spring treatment on subsequent ryegrass density.

Strip	1996 treatment of wheat crop	Ryegrass m^{-2} in 1997
1	Silage produced, regrowth killed with paraquat.	110
2	Hay produced.	1,200
3	Harvested for grain.	3,310

Table 2. Weed management of block 1A York, WA.

Year	Weed treatments (silage cut 1996)	Cumulative ryegrass m^{-2}	Gross margin \$ ha^{-1}
1997	Spray.Seed®[A], “tickle”[B], Spray.Seed®, barley, late sown with full cultivation, trifluralin, harvest[C]	110	450
1998	Burn barley trails, tickle, Spray.Seed® canola sown with full cultivation, Fusion®[D], harvest[C]	84	Poor crop -56
1999	Burn canola trails, Spray.Seed®, wheat late sown at 100kg ha^{-1} with full cultivation, no grass selective herbicide, harvest[C]	124	Poor crop 7
2000	Burn wheat trails, tickle, field pea late sown with full cultivation, diuron + imazethapyr, paraquat at Zadoks 80 of ryegrass[E].	295	Not available
		Cumulative gross margin	\$401

[A] Spray.Seed® trademark of Cropcare = paraquat + diquat.
[B] Tickle = light pre-sowing cultivation to stimulate weed seed emergence.
[C] Harvest, narrow chaff trails created which confines weed seed to narrow bands.
[D] Fusion® trademark of Cropcare = fluazifop-P + butoxydim
[E] Referred to as “crop topping”

Table 3. Weed management of block 2D York, WA.

Year	Weed treatments (hay cut 1996)	Cumulative ryegrass m^{-2}	Gross margin $ $ ha^{-1}$
1997	Sown to clover[A] pasture, ryegrass sprayed with paraquat at Z80[B]	860	-79
1998	Clover pasture, paraquat at Z80.	24	64
1999	Spray.Seed®, wheat, 100 kg ha^{-1} late sown full cultivation no grass selective, harvest[C]	8	496
2000	Burn wheat trails Spray.Seed® wheat, late sown at 100 kg ha^{-1}, no grass selective herbicide, harvest[C]	28	Not available
		Cumulative gross margin	$481

[A] Clover is *Trifolium subterraneum.*

[B] Referred to as "pasture topping".

[C] Harvest, narrow chaff trails created which confines weed seed to narrow bands.

Young

The second demonstration presented was conducted at Young, NSW. This site when first inspected carried a failed triticale crop (*Triticosecale* spp.) infested with dense annual ryegrass (2000 m^{-2}). The ryegrass was known to be resistant to diclofop and chlorsulfuron. The producer still had access to herbicides such as clethodim, trifluralin, and simazine. The object of this demonstration was to reduce ryegrass numbers so that the effective herbicides would not be exposed to large weed densities. In addition, gross margin data were calculated for each management option.

In contrast to the York site, this demonstration had only four plots each of 0.5 ha (Plots 1-4). Management details of plot 1 are shown in Table 5 while those for plot 4 are shown in Table 6. The balance of the field (15 ha) was treated with "best bet" management (Table 4). Since the initial triticale crop was a complete failure, there was no harvest option as there was at York, so the treatment options were more limited.

Table 4. "Best bet" management of 15 ha at Young, NSW.

Year	Weed treatment	Ryegrass m^{-2}	Gross margin $ ha^{-1}
1997	Failed triticale cut for silage.	2,000	n/a
1998	Glyphosate pre-sowing spray, annual legume pasture mix[A] sown, glyphosate applied prior to silage cut.	216	59
1999	Glyphosate pre-sowing spray, legume pasture mix[A] sown, pasture grazed then cut for silage. Pasture regrowth cut for hay.	8	454
2000	Pre-sowing glyphosate, TT canola min. till seeded, triazine herbicides applied. Crop swathed prior to sowing and straw spreader disconnected on harvester. Straw trails burned.	10 (0 at Z80)	Estimated yield 2.5 t ha^{-1} 500
		Cumulative gross margin	$1013

[A] The pasture mix includes three clovers: berseem (*Trifolium alexandrinum*) arrowleaf (*T. vesiculosum*) and Persian (*T. resupinatum*) and is a result of research conducted by NSW Agriculture.

Table 5. Weed management of Plot 1 Young, NSW.

Year	Weed treatment	Ryegrass m^{-2}	Gross margin $ ha^{-1}
1997	Failed triticale cut for silage.	2,000	n/a
1998	Glyphosate pre-sowing spray (July), trifluralin applied, lucerne[A] seeded, clethodim applied.	216	-143
1999	Lucerne pasture grazed, then ryegrass escapes treated at Z80.	8	498
2000	A continued lucerne phase would have been desirable. Sown to TT canola with the rest of the area.	10 (0 at Z80)	Est. 500
		Cumulative gross margin	$855

[A] Lucerne, *Medicago sativa L.*

Table 6. Weed management of Plot 4 Young, NSW.

Year	Weed treatment	Ryegrass m^{-2}	Gross margin $ ha^{-1}
1997	Failed triticale cut for silage.	2,000	n/a
1998	Pre-sowing glyphosate, grazing triticale min till seeded, grazed then killed in spring with glyphosate.	216	135
1999	Pre-sowing glyphosate, triticale residue burned, trifluralin applied, field pea seeded in June.	8 (0 at Z80)	527
2000	Wheat would have been appropriate, but the area was seeded to TT canola with the rest of the area.	0	Est 500
		Cumulative gross margin	$1,162

Even though this site is much less complex than the previously described York site, it clearly demonstrated methods of reducing large weed densities prior to using selective herbicides. For example, the trifluralin in plot 4 was only exposed to 8 ryegrass m^{-2} (Table 6) and the triazine herbicide in all areas was applied to around 10 ryegrass m^{-2} in 2000 (Tables 4, 5 and 6).

Wallacetown

The third site is at Wallacetown, NSW and is included simply to show that there are a range of options for demonstrating integrated weed management. In that case, the producer had diclofop and fluazifop-P resistant wild oat (*Avena* spp.) patches of up to 2000 plants m^{-2} through the field. The field was sown to pasture for enough time to deplete the wild oat seedbank. The farmer sowed most of the field to lucerne pasture with a companion wheat crop (Table 7). The remainder of the field was sown to various legumes with no crop (Table 8) and managed separately.

The advantage of growing wheat with the lucerne is that the farmer will realize a positive return in 2000. The disadvantage is that it required a herbicide to be applied to a large numbers of wild oats, with no viable options for controlling escapes. This will result in high weed pressures in 2001 that may retard the establishing pasture. More importantly, high weed seed production will increase the seedbank. In contrast, the legume strips were productive and will be brown manured (brown manure describes manuring using a herbicide to distinguish it from green manuring which is achieved with cultivation). Even though this will not produce the same income as the wheat for 2000, weed management has been non-selective and seed production will be greatly reduced. These strips could have been ensiled for better economics and similar weed management.

Table 7. Weed management of field at Wallacetown, NSW.

Year	Weed treatment	Wild oat m^{-2}	Gross margin \$ ha^{-1}
2000	Stubble burned, area sprayed with glyphosate pre-sowing, sown with companion wheat crop and lucerne, wild oats treated with flamprop – methyl. Crop harvested normally.	Patches to 2,000	n/a
2001	Pasture managed to reduce weed densities		

Table 8. Weed management of demonstration at Wallacetown, NSW.

Year	Weed treatment	Wild oat m^{-2}	Gross margin \$ ha^{-1}
2000	Strips sown to annual legumes following pre-sowing glyphosate. One strip is vetch[A] and the other is the annual pasture legume mix[B]. Strips have been killed with glyphosate prior to seed formation (brown manured).	Patches to 2,000	n/a
2001	Forage oat will be sown.		

[A] *Vicia* spp.

[B] The pasture mix includes three clovers: berseem (*Trifolium alexandrinum*) arrowleaf (*T. vesiculosum*) and Persian (*T. resupinatum*).

South Australian farm survey method

The Alma and Tarlee Land Management Groups pioneered this method. In this method, producers monitor fields over time, tracking crop rotation, weed management practices, and seedbanks. All of the field details are then collated in an annual report. By having such a large number of fields, a wide range of systems can compared over a wide range of environments.

In contrast to the WA model where emerged seedlings are counted, the group chose to use soil sampling (in autumn) to directly measure seedbanks. In the survey, each producer was asked to collect relevant information from a minimum of two different fields. An employee of the group carried out seedbank sampling and a four-year record was collected from a total of 31 fields. One of the field records is summarized in Table 9. It's worth noting that the treatments are those chosen by the grower and are not necessarily considered optimal (for example, the three cultivations used in 1995).

Table 9. Weed management of TD Rudd's Dam Field, SA.

Year	Treatment	Ryegrass seeds m^{-2}	Gross margin \$ ha^{-1}
1995	Barley sown following three cultivations, glyphosate and trifluralin applications. Tralkoxydim applied in crop.	12,000[A]	297
1996	Pasture sown following one cultivation. Paraquat at Z80 of ryegrass.	20,000	73
1997	Pasture. Paraquat at Z80 of ryegrass.	8,000	32
1998	Details unavailable.	< 2,000	

[A] As measured in the autumn of that year.

The initial work carried out by the land management groups showed so much promise that a GRDC-funded project coordinated by Dr Gurjeet Gill of the University of Adelaide has been initiated to use the method in other areas.

Clearly, the SA survey method can potentially achieve similar results in terms of demonstrating IWM to the WA demonstration method.

The system would be improved if individual producers were asked to include some newer, or unusual treatments, so that more potential systems are compared.

Conclusion

The Australian extension effort has resulted in producers and agronomists being well educated about the causes of resistance and increasingly, with the aid of demonstrations, possible management options to address the problem. The impact of the demonstration work was strengthened by the fact that the basic messages are the same across the country, bearing in mind that there are regional differences. Producers are adopting IWM even though the degree to which they do is often related to the severity of their resistance problem.

Information from the demonstrations has provided advisers with a strong knowledge base on which to make recommendations. Importantly, the demonstrations form part of a strong feedback loop to research and have provided validation data for predictive models. The work has created a demand from producers for research into new weed control tactics, resulting in increased research funding.

Literature cited

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Pesticide-free production: a reason to implement integrated weed management

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Pesticide-Free Production (PFP™) crops are those bred using conventional techniques and that have not been treated with pesticides from the time of crop emergence until the time of marketing. In addition, such crops cannot be grown where residual pesticides are considered to be commercially active. This production system is being developed in Manitoba by researchers at the University of Manitoba, Manitoba Agriculture and Food, and Agriculture and Agri-Food Canada (Brandon) under the guidance of a farmer steering committee (Pesticide-Free Production Canada) and using farmer participatory and institutional research initiatives. In 2000, PFP was attempted in 65 fields in Manitoba; 47 of these were successfully certified PFP. The success of this system will require producers to adopt integrated weed management. The idea of PFP and the way in which it is being developed is discussed.

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Introduction

Integrated weed management (IWM) is designed to help producers reduce input costs and herbicide load on the environment. IWM has been supported by extensive research, but has not been widely adopted by producers (Norris 1992). The reasons for this problem are many (Czapar et al. 1997), but the most important reason is a disconnect between the goals and needs of academic researchers and the goals and needs of producers (Norris 1992). If it is accepted that IWM is a good thing and that its adoption rate among producers should increase, then there has to be a draw for producers to adopt IWM. The production of integrated pest management (IPM) or organic labelled products at a premium price over conventionally-produced commodities may fulfill this requirement. Pesticide-Free Production (PFP^{TM}) is an IPM approach to cropping that is being developed in Manitoba using producer involvement and direction. It may become a vehicle for greater adoption of IWM among mainstream crop producers.

Academic IWM

The benefits of reduced input costs for the producer and reduced herbicide load on the environment are desirable. These benefits have been used as the justification for many weed science studies in the area of IWM. A view held by some, however, is that IWM efforts on the part of weed scientists have resulted in very little practical progress in IWM. Norris (1992) proposed that this lack of practical IWM success was, in part, the result of IWM related studies being conducted with a herbicide bias (herbicide-based). He noted that critical period of weed control studies, for example, although considered to be IWM studies are designed around herbicide application timing (Martin et al. 2001, Van Acker et al. 1993). Even if these studies are conducted using mechanical or manual weed removal the weed control efficacy level is brought up to a level associated with broadcast herbicide use (Van Acker et al. 1993). A broader approach to the development of IWM would be to base it on the development of systems that are diverse and biologically robust; systems that are inherently less susceptible to weed invasion, proliferation and interference. A simple example may be the inclusion of perennials, such as alfalfa (*Medicago sativa* L.), into an annual crop rotation. This has proven to be a generally effective weed population suppression strategy (Ominski et al. 1999). This approach would not exclude herbicides but it would also not assume that herbicides would be available for use in the system. The academic development of IWM has followed the entomological approach to the development of IPM (Norris 1992) whereby prior to the advent of pesticides the emphasis in the development of insect control strategies was on understanding pest biology and ecology. When pesticides were developed, the emphasis in the development of insect control strategies was based around optimizing the use of pesticides. In the latest era there has been a realization that because of problems associated with pesticide use (environmental problems, resistance of pests, health concerns) the reliance on pesticides needs to be reduced and this requires the development of insect management approaches that are not pesticide based, but may not be pesticide exclusive. To be successfully adopted these new management approaches must, however, be created in the context of the practical realities, mind set, goals and needs of producers.

Low rates of producer adoption of IWM

Among mainstream crop producers IWM is not actively practised (Manitoba Agriculture and Food 1996; Czapar et al. 1997). This is due in part to the availability of biologically and economically effective herbicides. In the context of relatively profitable farming (adequate commodity prices to cover input expenses including herbicides, plus profit) the adoption of IWM will remain low despite the research effort. It is not just herbicide effectiveness, however, that prevents growers from adopting IWM practices. For example, economic thresholds for weed control have been recognized as a major component of IWM (Cousens et al. 1985), but their use rate is very low among producers, and in a survey in Illinois producers provided a number of reasons why they would not use thresholds (Table 1). This survey points to a need to conduct research in the area of the impact of weed seed return and weed dynamics. The survey also shows interesting differences in response between herbicide dealers and growers. The dealers were generally more concerned about field appearance than growers and growers had less concern about time for field scouting than did dealers. These results beg the question of whether dealer influence is a major limiting factor to grower adoption of IWM. It also suggests that producers may be more open to IWM than one might expect, and that they seem to be more open to use thresholds than are herbicide dealers. The lack of IWM adoption may also, therefore, be due to extension failure. In 1996, Manitoba Agriculture and Food, conducted wild oat (*Avena fatua* L.) and green foxtail (*Setaria viridis* L.) economic threshold demonstrations in collaboration with the Manitoba Weed Supervisors Association (Manitoba Agriculture and Food 1996). Their results showed that actual use of threshold models resulted in net losses due to improper recommendation not to spray, as often as they resulted in net gains from proper recommendations not to spray. This program was successful in exposing growers to the concept of economic weed control thresholds but it highlighted deficiencies in the specific case predictive accuracy of these models. This program was based on the goal of trying to help producers reduce weed control costs, but it may have done damage to the image of IWM among producers because it exposed them to the not fully developed nature of a single IWM tool, economic thresholds for weed control. This initiative, although done with good intentions, promotes herbicide-based IWM. It may be more important to the development of IWM to promote systems in which herbicides are less likely to be needed.

Table 1. Major limitations that would prevent growers and dealers from using economic thresholds for weed management (adopted from Table 1. Czapar et al. 1997).

Limiting Factor	Grower response	Dealer response
	%	%
Harvest problems due to weeds	64	60
Landlord concerns	38	55
Weed seed production	38	55
General appearance of field	36	75
Effect of growing season on weeds	22	7
Time required to scout fields	6	25
Lack of weed competition data available	6	10
Need to improve weed ID skills	7	11
	n = 271	n = 143

The growth of eco- and IPM-food labels

Business opportunities can drive change in agricultural practices. The green revolution developed an industrialization of agriculture to capture emerging export markets for primary commodities. The model of farming that came from the green revolution was geared towards maximizing production. This goal was established in the context of healthy export markets and it was fuelled by rapid growth in world population, and by relatively high commodity prices. As commodity prices fell under the weight of production success, farmers required subsidies to sustain farming systems that were becoming inherently economically unsustainable under the pressures of globalization (Conway 1997). At the same time that farmers were facing economic threat within the farm gate, increasingly educated and health conscious consumers in the developed world became interested in agricultural products produced under means that could be considered more natural. The demand for IPM and organic labelled produce is increasing steadily, with reports of sustained growth of demand for organic produce of 20% per year in the United States (personal communication, Katherine DeMatteo, Director, U.S. Organic Trade Association). Fear of pesticides is a major reason for consumer demand for these products and in an unprompted survey atmosphere 16% of US consumers identified pesticides as a food safety risk (Hoban 1999). Organic and IPM labelled commodities are presently sold for a premium and they are becoming an increasingly attractive opportunity for mainstream producers. Producers will have to practice non-herbicide based IWM to producer these commodities.

Pesticide-free production (PFP™)

What is pesticide-free production?

Pesticide-free production involves eliminating all synthetic pesticide use during the active growth phase of crop plants. The definition we have created for PFP is: crops bred using conventional techniques, that have not been treated with pesticides from the time of crop emergence until the time of marketing. In addition, such crops cannot be grown where residual pesticides are considered to be commercially active. PFP is subject to specific rules which can be found at www.pfpcanada.com.

The current crop production system in Manitoba and western Canada is based on a model of high commodity prices. This model may not be appropriate for current market realities. The result of low commodity prices has been an increase in farm size where economies of scale can be captured. Over time, this trend has meant reduced net returns per acre, greater “industrialization” of the crop production sector, and reduced grower control of the production system. To remain economically viable under these conditions farmers can diversify into new markets, increase income per acre and decrease costs per acre.

A pesticide-free production (PFP) system will enable farmers to reduce input costs and to tap into a potential new market for their existing crops, thereby increasing net income per acre. Manitoba farmers are in a particularly good position to incorporate PFP into their farming systems because of generally favourable climatic and soil conditions, superior grower management skills and a “track record” in marketing superior quality grains around the world. If growers in Manitoba dedicated, for example, 20% of their acreage to PFP, and assuming that PFP increased returns by $20 per acre, and reduced input costs by $20 per acre, the net income gain directly to Manitoba farmers would be $100 million per year. In addition, by encouraging producers to achieve pest control by means other than the use of pesticides, PFP allows producers to be less reliant on external inputs for crop production giving them more personal control over their crop production.

Reasons for adopting pesticide-free crop production systems

There are several reasons why pesticide-free or pesticide-reduced crop production systems are worth pursuing, from a research, production and marketing standpoint:

1. Consumers are increasingly concerned about the environment, and how primary industries such as forestry, fishing and agriculture affect the environment. Pesticide-free and pesticide-reduced food products will be well positioned to fill a gap in consumer demand (between organic and conventional), and act as a system which can be more readily adopted by the majority of producers in Manitoba.

2. Growing crops in a pesticide-free environment will create new markets for existing (old) crops. In this way, old crops can be adapted to become new crops. This represents a unique form of diversification (diversification within traditional crops) for Manitoba farmers, and builds on existing strengths and abilities within the Manitoba grain sector.

3. Pesticide use has serious problems and limitations: a) consumers perceive pesticides to be a threat to personal health, b) some pesticides represent an environmental hazard as reflected in recent US decisions to ban many pesticides from use in food products (eg. Lindane for canola), c) because of the vertical integration within the pesticide-seed industries, reliance on pesticides means reduced control by farmers of their crop production system. Pesticide-free production will empower farmers to take control of their production systems and a greater portion of the generated wealth will stay within the region, and d) pesticides do not control insect, weed and disease pests as well as they used to because of organism resistance to pesticides. Pesticide-free production will allow producers an opportunity to learn how to control pests in a “no-pesticide option” scenario and it will offer them a financial premium while they obtain this knowledge.

4. To be successful, pesticide-free and pesticide-reduced crop production systems must be knowledge and management intensive. Solutions to pest problems will, to a significant extent, be addressed through locally developed cropping systems. This will create employment for both farm advisors and innovative product development at the local level.

Approach to developing PFP

Project steering committee

In the fall of 1999, a steering committee of farmers representing all agricultural eco-regions of Manitoba was established to provide input into the PFP project. The steering committee has been called Pesticide-Free Production Canada and it meets with the research team several times during the year to plan and evaluate the progress of the project.

Farmer participatory research program

The intention in the PFP program was that farmer involvement would not be limited to serving in an advisory capacity. Participatory research has been proven highly effective for getting farmers to understand and adopt new farming practices (Chambers, 1997). The objectives of the participatory research program were to establish contact with producers interested in practising PFP and to characterize their PFP fields in terms of pest levels and agronomic practices past and present on the field. As well, the intention is to characterize the farm scenario in terms of the demographics and the social philosophy of the farmers involved in the program. This information is used to place those who practice PFP in the context of all producers and, from this, to develop tailored extension plans. All farmers will be invited to annual winter meetings where the results of the participatory and institutional research will be discussed.

Institutional research programs

The foci of the institutional research efforts will be 1) to develop biologically robust production systems that are less susceptible to pest invasion, proliferation and interference. These systems will allow for adoption of PFP, 2) to develop non-pesticide approaches to pest control, and 3) to aid market development for PFP crops.

Multi-year rotational experiments have been established at Brandon, Carman and Glenlea, MB, and have been designed to consider the effect of including PFP years within the rotation on the successful management of pests. These rotation experiments focus on the inclusion of diversity of crop type (growth habits and competitive nature) and the inclusion of perennials, the intensity of weed control and the frequency of PFP on the success of PFP in any given rotation.

Several issues to be considered will not be adequately addressed within the rotational studies. Therefore, additional research will be conducted on a) the control of winter annual weeds in zero-tillage PFP, b) the value of delayed seeding and fall seeding for the avoidance of weed, disease and insect pressure, c) tillage for weed control, d) pest resistant crops, and e) intercropping.

The potential for PFP crops in the marketplace, as well as the logistics of positioning PFP crops to consumers, is being investigated. We recognize that producers are attracted to the PFP idea because it may bring premium value crops into their rotations. We also recognize that this premium is dependent upon identifying and fulfilling markets for PFP crops and value-added products. A number of producers have independently created the Pesticide-Free Production Farmers' Co-op to market PFP crops and products. The University of Manitoba has acquired trademark rights to Pesticide-Free Production to prevent private companies from controlling the trademark at cost to producers.

Implementing PFP in Manitoba - preliminary results from year 1

To bring producers to the participatory research program we advertised in local newspapers around Manitoba and had producers call a toll-free line to sign up. We had 68 producers sign up at the beginning of this year. A total of 45 fields were certified as PFP in Manitoba in 2000 (Table 2) according to the rules for PFP defined by PFP Canada. These fields included 10 different crop species, although the majority of fields (74%) were in four crops only: oats, wheat, barley and fall rye. This was expected given that cereal crops tend to be more competitive with weeds than broadleaf crops such as flax and canola. Oats was expected to be selected because no wild oat herbicide options are available and producers are, therefore, comfortable growing oats without herbicides. Fall rye and barley (non-malting) were expected to be included because they are weed-competitive crops, and because they are considered low value crops they are commonly grown with few pest control inputs. We expected a higher percentage of the attempted winter wheat fields to make it through to certification (only 17% did, Table 2) but spring weather conditions were conducive to early occurrence of cereal leaf diseases and many winter wheat fields were sprayed with a fungicide. No canola fields were certified PFP because all fields were planted with treated canola seed. Most fields that failed to receive certification were sprayed for weed control. In Manitoba, 98% of cereal fields (wheat, oats and barley) and 100% of oilseed fields (canola and flax) are normally sprayed with herbicide (Thomas et al. 1999). Weed density in certified PFP fields tended to be lower than attempted PFP fields (Table 3). Certified PFP fields had higher residual weed densities than non-PFP fields across Manitoba, according to the 1997 Manitoba weed survey (Table 3).

Farmers involved in the development of PFP are very interested in gaining a market for PFP crops and in creating some mechanism whereby they can capture and maintain a premium for these crops. At present they are exploring the creation of a price discovery mechanism through a farmers' co-op which would serve the purpose of helping individual producers to set a relatively common bargaining position with buyers. This system would be less restrictive than closed co-op systems which require single position selling. When polled most producers claimed that they were drawn to the concept because they had successfully achieved PFP in the past for reasons of cost cutting, and all felt confident that they could achieve it again.

Table 2. Number of attempted and certified Pesticide-Free Production (PFP™) fields in Manitoba in 2000.

Crop	Number of attempted	Number of certified	Total certified
	PFP fields		PFP hectares
Oats	15	12	392
Wheat	14	9	383
Barley	11	6	166
Fall Rye	8	8	213
Winter Wheat	6	1	8
Flax	4	4	137
Buckwheat	3	3	22
Canola	3	0	0
Hemp	71	1	17
Soybean	1	1	20
Total	66	45	1358

Producers who participated in 2000 will be surveyed for demographic, agronomic and sociological information so that we may gauge the position of these farms within the context of farms within Manitoba. This information will also provide an indication of whether producers are actively implementing practices to achieve PFP or whether they are merely hoping to achieve PFP in a given year. We will record what producers did with fields that were PFP in 2000 to assess whether they were treated differently in succeeding years. We also want to determine if PFP success is more likely for producers who have a systems approach and not a pesticide approach to pest management.

PFP has been incorporated into ongoing agronomy trials being conducted by M. Entz at Carman and Glenlea, MB. At Carman, yield of oats in PFP and non-PFP treatments were similar (Table 4). At this site, oats followed a rotation of wheat-flax-wheat which had previously been in alfalfa for five years. Alfalfa, even four seasons after its termination, may have contributed to low weed densities in these plots (Ominski et al. 1999). At the Glenlea site, the non-PFP treatments provided significantly higher yields (16-20% higher than PFP) (Table 4). This site had relatively low weed pressure (no graminicide was applied to the non-PFP treatments) and the higher yields in non-PFP treatments was attributed to the application of fungicide to control cereal leaf diseases. The economic differences between treatments has not yet been determined, but the potential for PFP was promising in these studies even though they were not conducted in rotations specifically designed to facilitate PFP.

Table 3. Average weed density on all attempted and certified Pesticide-Free Production (PFP™) fields in Manitoba in 2000 and for selected crops, comparison to average weed density per field as found in the 1997 Manitoba weed survey (Thomas et al. 1998). Values in parentheses are standard errors of the mean.

Crop	Attempted PFP fields	Certified PFP fields	Weed survey
	Plants m^{-2}		
Oats	145 (163)	136 (143)	105[c]
Wheat	155 (108)	111 (73)	73
Barley	92 (212)	54 (132)	56
Fall Rye	74 (103)	74 (103)	
Winter Wheat	56 (111)	27 (—)[a]	
Flax	60 (32)	60 (32)	39
Buckwheat	100 (35)	110 (35)	
Canola	129 (97)	---[b]	34
Hemp	110 (—)	110 (—)	
Soybean	24 (—)	24 (—)	
Average for all crops	132	103	61

[a] Only one field, thus a standard error could not be calculated.

[b] No canola fields were certified as PFP in 2000 due to seed treatment.

[c] No standard errors available from 1997 survey, and values not available for all crops.

PFP rotation studies were newly established at Carman and Brandon, MB. At the Carman site the rotations reflect two extremes of biological robustness. One rotation is a typical annual crop rotation (oats-flax-wheat-canola). The other includes two years of alfalfa in a 4-year rotation (oats-alfalfa-alfalfa-canola). PFP crops are placed into these rotations at a frequency of either 1 year in 4 or 2 years in 4. No other particular treatments will be applied to favour PFP.

Table 4. Oat (cv. AC Assiniboia) and hard red spring wheat (cv. AC Barrie) yields in Pesticide-Free Production (PFP™) and non-PFP treatments on crop rotation studies conducted at Carman and Glenlea, Manitoba in 2000 (data from research program of Dr. Martin Entz - University of Manitoba).

Treatment	Carman Trial 1[a] (Oats)	Carman Trial 2[a] (Oats)	Glenlea[b] (Wheat)	Glenlea[c] (Wheat)
	kg ha^{-1}			
PFP	4538	4815	2546	2291
Non-PFP	4471	4828	3055	2768
LSD (0.05)	NS	NS	441	441

[a] Oats following alfalfa (5 years)-wheat-flax-wheat, bromoxynil + MCPA applied to non-PFP.

[b] Wheat following canola, bromoxynil + MCPA and foliar fungicide applied to non-PFP.

[c] Wheat following canola-oats, bromoxynil + MCPA and foliar fungicide applied to non-PFP.

At the Brandon site, an annual rotation (oats-wheat-canola) has been set up with PFP practised 1 in 3 years (always in oats). Treatments with various levels of weed control intensity have been overlayed on this rotation, with the most intensive treatment including chaff collection in all years and intensive herbicidal weed control in non-PFP years. For this trial the PFP target crop is oats and in this first year, no significant differences were found between the conventional and the PFP treatments in terms of weed biomass in August, oat yield, dockage in oats and oat thousand kernel weight (data not shown).

An established rotation study at Glenlea, MB also contains PFP. This rotation study has three basic rotations ranging from simple annual to two of four years in alfalfa. Overlayed on the rotation is a factorial design of treatments where pesticides (p) or fertilizer (f) are included or not included (+p+f, +p-f, -p+f, -p-f). In this study, PFP is tested in the context of the relative biological robustness of a given cropping system, and additionally, within the context of using or not using additional fertilizer. This rotation has been running for 9 years. In the eighth year all plots were planted to flax and weed infestations were assessed. Weed densities were significantly lower in rotations containing legume forages (sweet clover plough-down or 2 years of alfalfa). Flax yields in the alfalfa rotation without either pesticide or fertilizer applied, were similar to flax yields in the annual rotation when both fertilizer and pesticides were applied. This demonstrates that a biologically robust cropping system is less dependent upon external inputs. This sort of system would be much more reliably suited to PFP than would a traditional annual crop rotation. The biologically robust system is an example of non-herbicide based IWM.

Summary

Under broad consideration, integrated weed management (IWM) should be designed to be economically, environmentally and socially acceptable (Swanton and Murphy 1996). Much academic consideration has been given to the concepts of IWM and to IWM as a component of integrated pest management. IWM remains a goal of weed scientists and it is consistently promoted within the academic weed science community (Hall et al. 2000). Farmers, however, are not adopting IWM. Pesticide-Free Production (PFP) is an initiative which appeals to farmers because it may mean new markets for traditional crops and sale of these crops at a premium price. To achieve sustained success, PFP will require IWM. PFP is, therefore an incentive for producers to adopt IWM. The manner in which PFP is being developed, via a farmer steering committee and farmer participatory research, helps to ensure that PFP suits the farmers' needs and goals, and is used by farmers. It will also encourage farmer interest in IWM. As researchers we must develop IWM systems that suit farmers' needs and goals.

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Implementing integrated weed management in barley (*Hordeum vulgare*): a review

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Integrated weed management (IWM) can be defined as the integration of several approaches, including herbicide application, to reduce the negative impact of weeds on crops. Agronomic practices that improve crop health by making the crop more competitive with weeds can be important components of IWM systems. A crucial first step is the selection of a competitive crop and variety. Of the main field crops grown in western Canada, barley (*Hordeum vulgare*) has been shown to be the most competitive with weeds such as wild oat (*Avena fatua*). The implementation of IWM should thus be more feasible in barley than in less competitive crops; however, barley varieties can vary considerably in their ability to compete with wild oat. Assessment of five varieties indicated that the relatively tall general-purpose varieties, AC Lacombe and Seebe, were better competitors than semi-dwarf or hull-less varieties and would thus be most suitable for IWM systems. Competitiveness of all varieties improved with increased seeding rates. Adopting agronomic practices that promote rapid emergence of barley seedlings from the soil should further improve competitiveness with weeds. Yield loss was reduced when barley emerged ahead of compared to after wild oat. The likelihood that barley will emerge ahead of weeds can be promoted by placing high quality seed relatively shallowly as soon as possible after a tillage operation or pre-seeding burn-off. In addition, banding rather

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than broadcasting nitrogen fertilizer was shown to improve competitiveness of barley and other crops over weeds. Implementing these practices may reduce or eliminate the need for herbicide application in a specific growing season. Regression models were developed to assist in determining whether wild oat control with herbicides in barley is economical, and how much wild oat seed is produced in the absence of herbicide application. The models are based on wild oat density, crop density, and relative time of emergence of the crop and wild oat. The models were tested in farmers' fields and were shown to be reasonably accurate in estimating yield loss, economic returns, and wild oat seed production. Our studies also showed that seeding barley at relatively high rates can result in optimum barley yields, undiminished economic returns, and effective wild oat management when tralkoxydim was used at lower than recommended rates.

Introduction

Interest in integrated approaches to weed management is being driven by declining crop prices coupled with increased input costs, consumer concerns about the environmental and health effects of herbicides, and increasing incidences of weeds becoming resistant to herbicides. Reduced dependence on herbicides can be achieved by adopting an integrated weed management (IWM) program. IWM essentially means the integration of several practices, including herbicide application, to reduce the negative impact of weeds on crops. The approach to IWM can be long- term, short-term, or a combination of both. The long-term strategy involves adopting a systems approach to weed management such as the implementation of appropriate crop rotations, companion cropping, growing crops for silage, introducing classical biological control agents etc. A more short-term approach involves improving seed yield of a specific crop by adopting agronomic practices that would enhance its competitiveness with weeds. This presentation will focus mainly on this short-term approach which should be considered as just one component of a long-term integrated crop management system.

Most of the focus will be on barley and wild oat. Barley has been shown to be the most competitive of the main field crops grown in western Canada (Dew 1972; O'Donovan 1988), and would be conceivably more suitable for implementing IWM than less competitive crops. Wild oat is the most serious annual weed of field crops in western Canada. In spite of extensive herbicide use over the last 30 years, it remains one the most ubiquitous weeds on the Canadian prairies. Weed surveys conducted in Alberta in 1997 (Thomas et al. 1998) indicated that wild oat occurred in 56% of fields surveyed, which is higher than previously reported. Part of the reason for this increased frequency may be that wild oat has developed resistance to many of the herbicides that once provided effective control (Heap et al. 1993; O'Donovan et al. 1994). It is crucial, therefore, to manage wild oat in an integrated fashion, and to alleviate crop losses and wild oat seed production by methods other than exclusive dependence on herbicides.

Adopting agronomic practices that give the crop a competitive advantage

Selecting a barley variety and seeding rate to optimize competitiveness

Field experiments were conducted at Vegreville, Alberta in 1997, 1998 and 1999 and Lacombe, Alberta in 1997 and 1999 to determine the influence of barley variety and seeding rate on interference of wild oat with barley (O'Donovan et al. 2000). The varieties grown were Falcon (hull-less, semi-dwarf, 6-row), Phoenix (hull-less, 2-row), CDC Earl (semi-dwarf, 2-row), AC Lacombe (6-row) and Seebe (2-row). Seeding rates were 85, 145 and 200 kg ha^{-1}.

Barley variety and seeding rate affected barley density, height at maturity and seed yield, and wild oat shoot dry weight and seed yield, in most experiments, but there was no variety x seeding rate interaction. The shortest varieties were Falcon and CDC Earl (data not shown). Barley seedling emergence and subsequent plant densities varied among varieties, locations and years (data not shown). In most cases, the hull-less variety, Falcon, had the poorest emergence while AC Lacombe and Seebe had the highest emergence. Wild oat seed production was highest in the Falcon and CDC Earl plots, suggesting that these were the least competitive with wild oat (Table 1). Barley yield loss from wild oat interference also tended to be highest in these varieties. Poor emergence of Falcon and the shorter stature of Falcon and CDC Earl, likely contributed to their relatively poor competitiveness with wild oat. Poor seedling emergence of the hull-less varieties occurred even though seed size and percentage germination of each variety was considered when establishing seeding rates. In hull-less varieties, the hull becomes detached during threshing. This makes the seed more vulnerable to mechanical damage and invasion by fungi (White et al. 1999), which probably accounted for the lower plant densities of the hull-less varieties in our experiments.

Increasing the seeding rate improved the competitiveness of all varieties as evidenced by reduced wild oat shoot dry matter and seed production and, in some cases, improved barley yields (Table 2). This result is in general agreement with that of a previous study where, in the presence of wild oat competition, barley yield loss decreased as seeding rate increased to 200 kg ha^{-1} (O'Donovan et al. 1999).

The results of the study indicate that barley varieties commonly grown in western Canada differ in their ability to compete with wild oat. The varieties AC Lacombe and Seebe consistently reduced wild oat seed production most effectively, and would be most suitable for IWM systems. Seeding AC Lacombe or Seebe at relatively high rates may minimize the need for wild oat control with herbicides. Conversely, the study emphasizes the need for effective weed control in the less competitive hull-less and semi-dwarf barley varieties before maximum yields could be achieved. The hull-less variety Falcon was particularly sensitive to weed competition due to both the semi-dwarf stature and relatively poor seedling establishment. Consistent establishment of these varieties at densities appropriate for optimum weed suppression may be difficult unless seeding rates are increased above those suggested by seed size and germination tests.

Table 1. Relationship between barley variety and wild oat seed production at Vegreville. Data represent averages of three barley seeding rates.

Year	Variety	Wild oat seed m^{-2}
1997	Falcon	2100
	Phoenix	720
	AC Lacombe	660
	Seebe	540
	CDC Earl	1500
	LSD ($p \leq 0.05$)	540
1998	Falcon	2760
	Phoenix	1860
	AC Lacombe	840
	Seebe	660
	CDC Earl	1320
	LSD ($p \leq 0.05$)	540
1999	Falcon	2280
	Phoenix	1380
	AC Lacombe	900
	Seebe	960
	CDC Earl	1980
	LSD ($p \leq 0.05$)	360

Adapted from O’Donovan et al. (2000).

Table 2. Relationship between barley seeding rate and wild oat seed production. Data represent averages of five barley varieties[a].

Year	Seeding rate (kg ha^{-1})	Wild oat seed m^{-2}
1997	85	1680
	145	960
	200	600
1998	85	2280
	145	1440
	200	1020
1999	85	2340
	145	1380
	200	1020

[a]Each year, response to barley seeding rate was significant at $p \leq 0.05$.

Adapted from O’Donovan et al. (2000).

Ensuring rapid emergence of barley seedlings

Field experiments conducted at Lacombe and Vegreville, Alberta in the 1970’s and 1980’s showed that early emerging wild oat caused the greatest yield losses in barley and other field crops (Cousens et al. 1987; O’Donovan et al. 1985). Yield loss in barley varied from 17% when wild oat emerged five days before the crop to only 3% when the crop emerged five days before wild oat (Table 3).

By striving to ensure that crops emerge as early as possible ahead of weeds, producers can maximize crop yield and minimize financial losses, and weed seed production. Early crop emergence can be promoted by planting vigorous crop seed at relatively shallow depths when the seedbed is moist and firm (as is often the case in zero tillage systems). The crop can also be given an advantage by seeding as soon as possible after the last tillage operation in a conventional tillage system, or pre-seeding herbicide application in a reduced tillage system. Otherwise, weed seed present in the soil may begin germinating even before the crop is planted.

Table 3. Effect of relative time of emergence of wild oats (20 plants m^{-2}) on yield loss of barley. Data are estimates from a regression model.

Time of wild oat emergence relative to barley	Barley yield loss (%)
5 days before	17
3 days before	13
1 day before	9
Same time	8
1 day after	6
3 days after	4
5 days after	3

Adapted from Cousens et al. (1987).

Placing fertilizer to favor the crop over weeds

Both crops and weeds compete for nutrients (e.g. nitrogen, phosphorus) present in the soil. Several studies have been conducted over the years to determine if the addition of extra nitrogen can reduce competition from weeds. The results have not always been as expected. In many cases added nitrogen benefited the weed over the crop. For example, in experiments conducted in California, wild oats were better able to utilize added nitrogen than wheat (*Triticum aestivum*), and therefore gained a competitive advantage over the crop (Carlson and Hill 1986). Likewise, researchers at North Dakota State University reached a similar conclusion with green foxtail (*Setaria viridis*) (Peterson and Nalewaja, 1992). Doubling the nitrogen rate did not increase wheat growth, but increased green foxtail weight by 41%. In both experiments, the nitrogen was broadcast on the soil surface and incorporated.

Several other studies have indicated that banding rather than broadcasting fertilizer can favor the crop. In wheat growing under zero tillage, there were 27-57% less wild oat plants when nitrogen fertilizer was band-applied in the seed row compared to broadcast-applied prior to seeding the wheat (Reinertsen et al. 1984). Likewise, Blackshaw et al. (2000) showed that an IWM approach that included banding nitrogen may allow producers to manage foxtail barley (*Hordeum jubatum*) successfully in wheat grown under zero tillage. Normally, this weed is very difficult to manage in reduced tillage systems. Deep banding compared to surface broadcasting nitrogen reduced foxtail barley biomass and increased wheat yield by up to 58%. Several other weeds were also shown to decline considerably in wheat when nitrogen was banded rather than broadcast (Kirkland and Beckie 1998).

There is also increasing evidence that deep banding nitrogen is an important IWM strategy in barley. In an unpublished study, there was 28-60% less wild oat shoots when nitrogen fertilizer was band compared to broadcast-applied in spring barley (D. Thill, University of Idaho, personal communication). In studies conducted near Vegreville, Alberta, a combination of judicious herbicide application, zero tillage, and deep-banded nitrogen reduced green foxtail populations to very low levels after four years of continuous barley (O'Donovan et al. 1997). Green foxtail populations were lower overall in the zero tillage system, and declined considerably with increasing nitrogen rate in both conventional and zero tillage systems (Table 4).

Table 4. Effect of banded nitrogen and tillage on green foxtail populations at Alliance, Alberta. Data were averaged over 1991 and 1992.

Nitrogen rate (kg ha^{-1})	Conventional tillage		Zero tillage	
	Emerged m^{-2}	[a]Seedbank kg soil^{-1}	Emerged m^{-2}	[a]Seedbank kg soil^{-1}
0	205	77	113	67
60	42	16	14	7
120	31	14	3	2
180	14	10	3	2

[a]Data represent number of seedlings that emerged in a kg of soil.

Adapted from O'Donovan et al (1997).

Determining if wild oat control with a herbicide is still required

Predicting yield loss

Scouting fields and assessing the nature and extent of the weed problem is an important component of IWM, especially when producers strive to enhance crop competitiveness in order to manage weeds. When implementing an IWM system, determining whether a herbicide application is still necessary will be an important requirement. Applying the "economic threshold" concept to weeds is not an easy undertaking (Cousens 1987; Norris 1992; O'Donovan 1996a). On the other hand, applying herbicides when they are unnecessary can be a waste of time and revenue, and can lead to the development of herbicide resistant wild oat. Information is available to assist in the decision-making process. Mathematical models based on wild oat density were developed in the early 1970's to determine the effects of wild oats on yield loss of barley and other crops (Dew

1972). These models were later refined to incorporate important additional factors such as crop density, and the relative time of emergence of the weed and crop (Cousens et al 1987; O'Donovan et al 1985; O'Donovan et al. 1999). Some of the models are important components of computerized decision support systems that are being used to advise producers on the economics of wild oat control with herbicides (Derksen et al. 1996; O'Donovan 1996b). The following model estimates barley yield loss due to wild oat:

$$\text{Barley yield loss} = 1.63 * d / (e^{0.27 * t} + 0.0163 * d + 0.018 * c) \qquad 1)$$

where d = wild oat plants m^{-2}, t = relative time of emergence (days) of the wild oat and crop, c = barley plants m^{-2}, and e is the base of natural logs.

Experiments were conducted in farmers' fields sown to barley in 1997, 1998, and 1999 to evaluate the accuracy of the model (O'Donovan et al., unpublished). Nine barley fields were assessed over the three years. The model was reasonably accurate in predicting yield losses and net economic returns due to wild oat (Table 5). Correlation between actual and predicted losses was high ($r = 0.91$, $df = 7$, $p = 0.001$). The model underestimated yield loss in only one of the fields (Table 5). Herbicide application was uneconomical at the wild oat densities present in most of the barley fields. This is in contrast to wheat and canola (*Brassica napus*) fields where herbicide application was mostly economical (data not shown). The superior competitiveness of barley, coupled with its relatively low market price suggests that implementation of the "economic threshold" concept for wild oat management may be most feasible in barley.

Predicting wild oat seed production

Although herbicide application may not always be economical in relatively competitive crops like barley, many producers would be reluctant to let wild oat and other weeds go to seed since this may exacerbate weed problems in future years. We have recently developed a model that will estimate wild oat seed production at different wild oat and barley plant densities. The model, based on data collected from farmers' fields, is as follows:

$$\text{Wild oat seed } m^{-2} = d / (0.00033 * (d - 1 + 0.265 * c) \qquad 2)$$

where d = wild oat plants m^{-2}, and c = barley plants m^{-2}. It was not possible to incorporate a relative time of emergence parameter in the model since in most fields the barley emerged several days ahead of the wild oat. Model estimates indicate that wild oat seed production was strongly influenced by barley plant density, and was considerably less at higher seeding rates (Table 6). However, even at the highest barley plant density (250 plants m^{-2}), a single wild oat plant produced an estimated 46 seeds m^{-2}. This would be unacceptable to many producers. It should be kept in mind, however, that not all this seed would result in wild oat plants in future years. Some seed will end up as dockage, succumb to predators, a tillage operation or pre-seed burn-off, and/or an effective in-crop herbicide the following spring. Others will remain dormant in the soil for many years, their impact possibly becoming "diluted" with time. It should also be kept in mind that wild oat populations in cropland in western Canada have not been decreasing in spite of extensive herbicide application, and that complete elimination of wild oat seed from the soil seedbank is probably an unrealistic goal. The risk associated with seed production by uncontrolled wild oat should be weighed against the risk of selecting for herbicide resistant wild oat in future years.

Table 5. Actual and predicted barley yield losses due to wild oats in nine fields, and actual and predicted profit or loss following wild oat control with a herbicide[a].

Wild oat Plants m^{-2}	Relative time of emergence (days)[b]	% barley yield loss		$ profit (+) or loss (-) after wild oat control	
		Actual	Predicted	Actual	Predicted
28	+4	1	7	-$40	-$14
9	+2	0	2	-$45	-$37
8	+5	0	2	-$45	-$38
12	Same time	13	7	+$11	-$14
22	+4	8	5	-$27	-$34
57	Same time	24	22	+$41	+$34
14	+4	4	4	-$25	-$25
13	+4	3	4	-$28	-$22
28	+5	6	7	-$28	-$25

[a] Assumes a barley price of \$90 ton^{-1} and a herbicide + application cost of \$45 ha^{-1}.

[b] Number of days preceded by + sign indicates barley emerged before wild oats.

Table 6. Estimated seed produced by one wild oat plant at different barley plant densities.

Barley plants m^{-2}	Estimated wild oat seed m^{-2} [a]
100	114
150	76
200	57
250	46

[a] Estimates are from model 2.

Reducing herbicide rates below those recommended on the label

Rather than completely eliminating herbicides for weed control, interest among growers and researchers has focussed on reducing herbicide rates in an effort to increase profitability. Much of this research has concentrated on the effect of low rates of graminicides on wild oat control. In general, the effectiveness of lower than recommended herbicide rates on wild oat management has been variable, and influenced by factors such as wild oat density (Belles et al. 2000; Holm et al. 2000; Wille et al. 1998; Zhang et al. 2000), growth stage at which the herbicide was applied (Holm et al. 2000; Spandl et al. 1997; Stougaard et al. 1997), and time of day that the herbicide was applied (Stevenson et al. 2000).

There has been little research conducted to determine if a relationship exists between crop competitiveness with weeds, and the efficacy of herbicides applied at lower than recommended rates. Decreased suppression of annual dicot weeds in cereals with sub-recommended herbicide rates was partially offset by increased crop seeding rates (Salonen 1992). Similarly, wild oat control with a low rate of quizalofop was better at a relatively high canola seeding rate (O'Donovan and Newman 1996). It is conceivable, therefore, that crop competition may influence the effectiveness of lower than recommended rates of herbicides used for wild oat control.

The hypothesis that barley (cv Falcon) seeding rate would influence the effectiveness of lower than recommended rates of tralkoxydim was tested in field experiments conducted over three years at two locations (O'Donovan et al., unpublished). Reducing the herbicide rate to as low as 50% of that recommended did not compromise yield or economic returns (data not shown). There was, however, a consistent and highly significant seeding rate by herbicide rate interaction on wild oat seed production. The effects of tralkoxydim on wild oat seed production, especially at relatively low herbicide rates, were generally superior at the higher barley seeding rates (Table 7). These results suggest that seeding barley at relatively high rates can result in optimum barley yields, undiminished economic returns, and effective wild oat management when tralkoxydim is used at lower than recommended rates.

Table. 7. Effect of tralkoxydim rate, and barley (cv. Falcon) seeding rate on wild oat seed production.

Year	Tralkoxydim rate (% of recommended)	Barley seeding rate (kg ha^{-1}) 75	125	175	P values for linear effect of seeding rate
		Wild oat seed m^{-2}			
1997	0	2710	2090	1230	0.003
	25	288	126	86	0.06
	50	208	126	17	0.0001
	75	28	9	15	0.32
	100	28	17	3	0.06
1998	0	3124	1663	960	0.0001
	25	266	66	16	0.0001
	50	103	5	4	0.007
	75	10	11	4	0.53
	100	3	0	0.6	0.39
1999	0	3950	2258	1994	0.01
	25	450	219	31	0.01
	50	48	44	32	0.48
	75	6	0.3	0	0.07
	100	4	2	1	0.97

Summary and conclusions

IWM is most likely to be successful in a strongly competitive and healthy crop. Barley has been shown to be the most competitive of the principal field crops grown in western Canada, and thus should be the most suitable crop in which to implement the IWM concept. The successful implementation of IWM in barley will be further enhanced if a competitive barley variety is grown. Of a number of varieties assessed, the relatively tall general purpose varieties AC Lacombe and Seebe were the most competitive, while a semi-dwarf variety, CDC

Earl, and a semi-dwarf, hull-less variety, Falcon, were the least competitive. The ability of barley to compete with weeds such as wild oat can be further enhanced by planting high quality barley seed at relatively high rates, and by banding rather than broadcasting fertilizer. Adopting agronomic practices that ensure early barley emergence relative to the weed can also confer a major competitive advantage. For example, barley planted relatively shallowly into a moist and firm seedbed as soon as possible after tillage or a pre-seeding herbicide application will likely emerge ahead of the weeds, and the result will be less crop yield loss and weed seed production.

Each of the practices outlined above, when considered alone, may not be sufficient to provide adequate weed management. Combining these practices would be more successful, but it may still be necessary to determine if in-crop herbicide application is required. Scouting fields and assessing the nature and extent of the "residual" weed problem thus becomes an important component of IWM. A mathematical model has been developed to help determine when wild oat control with herbicides is economical in barley. This has undergone considerable evaluation in farmers' fields and has been found to provide accurate estimates of barley yield losses due to wild oat, and whether or not a profit or loss would result from a herbicide application. Herbicide application was uneconomical at the wild oat densities present in most of the barley fields. This was in contrast to wheat and canola fields where herbicide application was mostly economical.

Although herbicide application may not always be economical, many producers are reluctant to let wild oat and other weeds go to seed since this may exacerbate weed problems in future years. A model that will estimate wild oat seed production at different wild oat and barley densities has recently been developed. Wild oat seed production was strongly influenced by barley plant density, and was considerably less at higher seeding rates. However, even at the highest barley-seeding rate, a single wild oat plant produced up to 70 seeds m^{-2}. This would be unacceptable to many producers.

Producers interested in reducing input costs, but also concerned about weed seed production, are often tempted to reduce the herbicide rate below that recommended. This is not without risk, and can result in loss of weed control as well as financial losses. Increasing the seeding rate of Falcon barley improved the activity of tralkoxydim on wild oat seed production. At a given tralkoxydim rate, wild oat seed production decreased as seeding rate increased. This is a good example of integrating herbicide application with an agronomic practice, and indicates that herbicide effectiveness may be improved if the competitiveness and health of the crop is enhanced.

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Implementing integrated weed management in canola

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In a strict sense, integrated weed management (IWM) is not extensively practiced in canola. Herbicides dominate the tools used in canola weed management systems partly because researchers and industry have studied herbicides most extensively, and partly because herbicides offer simple and cost-effective, albeit short-term, solutions to difficult problems. The extensive and continued use of herbicides has led to ever-increasing cases of weed resistance to herbicides. IWM research should focus on combining several weed management tools into diverse cropping systems that focus on crop health. For example, weed management in canola is enhanced when competitive cultivars are augmented with higher seeding rates. In addition, practices such as seeding canola in the fall allows growers to introduce operational diversity that may leave weeds that are adapted to conventional seeding dates "unprepared" to compete and thrive. Ironically, because IWM must be integrated with all other crops and crop production practices that influence the ecosystem, the best thing a grower could do for IWM in canola may be in another crop. More IWM research should focus on why weeds are present rather than their management. Urban pressure to

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reduce pesticide use, herbicide resistance, and high input costs may push growers to adopt IWM and alternative weed management systems to a greater degree than they, or many weed researchers and agronomists, are currently comfortable with or prepared for.

Introduction

Adoption of IWM practices in canola is low and slow. Research on IWM in canola has been limited. A recent literature search (December 4, 2000) involving three major databases {AGRICOLA (1970-2000), AGRIS (1975-2000), and Biological Abstracts (1985-2000)} led to over 100 references in each database for IWM, but no references for IWM and canola. Weed scientists generally spend little time conducting or publishing IWM research (Thill et al. 1991), and though there is research involving components of IWM in canola, cropping systems employing IWM in the entire rotation have not been established. Swanton et al. (1991) suggest that IWM is broad enough that IWM research will require a multi-disciplinary approach. Indeed, Thill et al. (1991) defined IWM as “the integration of effective, environmentally safe, and sociologically acceptable control tactics that reduce weed interference below the economic injury level”. Perhaps IWM is so encompassing that few dare to claim that it is really researched or practiced. If we define IWM as weed management employing at least two management strategies (prevention, cultural, mechanical, biological, or chemical), then maybe IWM adoption could be claimed to be relatively high. Given the latter definition, IWM is probably being practiced by some growers in varying degrees in canola and other crops. Nevertheless, satisfying all of the qualitative parameters of the former definition is not only intellectually intimidating, but also very difficult in practice.

Science, advertising, expectations, and resistance

One reason for poor IWM adoption relates to research emphasis on herbicides. Weed science has focused on control technology as opposed to weed biology in agroecosystems (Wyse 1992). In other words, “technology has replaced cultural practices” (D. L. Beck, personal communication). Widespread and very effective advertising also persuades growers that “clean fields” are attainable with a single tool - the right herbicide treatment. The effectiveness and ease of use of high-efficacy herbicides has led many growers to believe that the advertisers are correct. In an era of low crop prices, when growers farm more and more land just for economic survival, quick and simple herbicide solutions have been very appealing. Over the last few years, Canadian growers have steadily increased their herbicide purchases to over $1 billion in 1999 (Crop

Protection Institute of Canada 2000). Unfortunately, the wide-spread adoption and continuous use of herbicide technology has also led to the rapid build-up of resistant weed populations (Heap 2001; Holt and LeBaron 1990), and in some areas, for weeds such as wild oat (*Avena fatua* L.), very few herbicide tools remain effective (Beckie et al. 1999).

Crop competitiveness and health

Another reason for poor IWM adoption in canola is that research and extension personnel have usually stressed single IWM tools as opposed to packages of tools in entire cropping systems. Increased canola seeding rate can aid in weed suppression (O'Donovan and Newman 1996), but is much more effective against weeds when combined with a competitive canola cultivar, shallow seeding, and fertilizer banded near the seed row. Figure 1 indicates that % dockage can be dramatically reduced with a competitive cultivar such as InVigor 2153 (G. W. Clayton, unpublished data). Perhaps more importantly, the data also illustrate that increasing the seeding rate of the competitive cultivar led to further significant reductions in % dockage. Technologies and information require "stacking" or "pyramiding" into packages that combine several strategies for superior crop health and competition with weeds.

Beck (2001) reminds us that "successful crop production, regardless of the methods used, is a careful piecing together of numerous components into a system. Simply replacing one component with another is seldom successful". Focusing on crop competitiveness and health will lead producers to rely on packages of tools which include such things as sanitation (prevention of weed seed spread), low disturbance seeding systems, higher seeding rates, narrow crop rows, optimum fertilizer placement, and diverse crop rotations. A healthy, competitive crop is the key to IWM in any cropping system.

IWM cannot be successfully implemented, and crop health cannot be achieved, if weed management is the exclusive focus of growers. If ignored, diseases, insects or other pests can reduce crop health to the degree that all of the tools employed for weed management are negated. For example, a canola crop with root systems ravaged by root maggots (*Delia radicum* L.) or brown girdling root rot (*Rhizoctonia solani* Kuhn) will not be healthy or competitive enough to crowd out weeds or even remain productive in the presence of relatively low weed populations. Crop health and competitiveness demand that all aspects of a healthy crop are considered and implemented. The importance of factors such as crop rotation, seed treatment, high seeding rates, fertilizer placement near the seed, and uniform seeding depth to final crop yields may be less than their importance to the augmentation of weed management (Beck 2001). Similarly, good disease and insect management, in some situations, may be more important for weed management, because of their impact on crop health, than for their direct effects on crop yield.

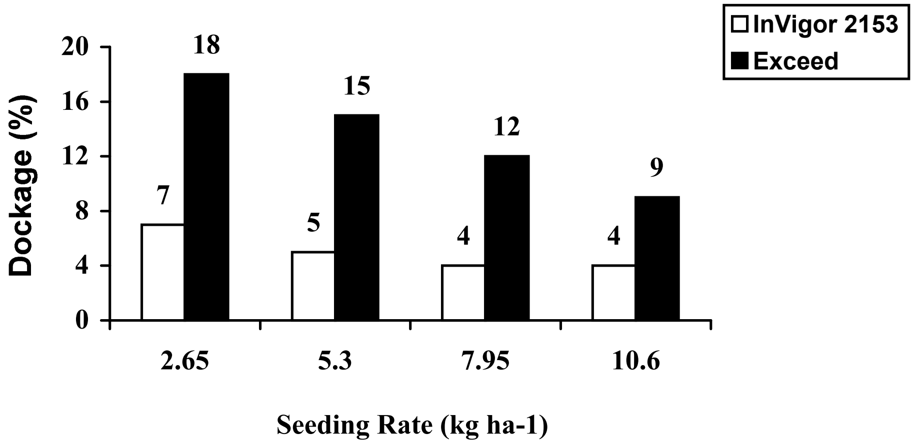

Figure 1. Cultivar ('InVigor 2153' versus 'Exceed') and crop seeding rate effects on canola (*Brassica napus*) dockage at harvest. Lacombe Research Centre, Lacombe, Alberta (Experiment 99013). LSD (0.05) = 2 for the difference among all means.

Cropping system diversity

Weed diversity is sufficient to successfully counter a variety of simple, repeated crop production practices (Blackshaw 1994; Dekker 1997; Harker 2000). The short-term, economic survival thinking involved in low diversity, short crop rotation sequences has likely created large niches in our cropping systems for weeds such as wild oat to thrive. Indeed, one might ask why a weed like wild oat, which has been the subject of constant attention and herbicide attack for the last few decades, continues to thrive? Ironically, it may be that we have focused too much on wild oat destruction as opposed to removing the niche that wild oat thrive in. That niche may be as simple as spring-seeded crops, seeded, sprayed, and harvested at relatively constant dates. Beck (2001) suggests that rotations containing plants of the same type with similar growth patterns (seeding and harvest dates) will develop weed problems from weed species with similar growth habits. Given year after year of the same practices, dominant weeds will increase sufficiently to thrive in simple cropping systems for many years (Buhler 1999; Dekker 1999). "A good rotation has diversity in plant types, planting dates, and harvest periods" (Beck 2001).

Seeding and harvest date diversity in fall-seeded canola

Fall-seeded or dormant-seeded canola has provided a new seeding date option for canola growers in western Canada over the past few years. In the 2000 growing season, approximately 2% of the canola harvested in Alberta was fall seeded (P. Thomas, personal communication). Benefits of fall-seeded or early spring seeded canola include earlier flowering (avoidance of hot, dry periods during flowering), a longer flowering period, earlier maturity, reduced plant height, higher oil content and up to 38% higher yields (Kirkland and Johnson 2000). Additional benefits of fall-seeded canola are less obvious than those mentioned above, but may be considerable in IWM cropping systems.

Weeds that have adapted to proliferate in crops seeded on conventional dates may be disadvantaged when required to compete with crops that emerge earlier in the season and are harvested earlier in the fall. Figure 2 shows canola phenology on June 26, 1999 when seeded in early November (1988), late April (1999), and in mid May (1999). On land subject to repeated seeding on standard dates, the bulk of the weed seedbank probably contains seeds that have been selected over many years to emerge just before or with crops seeded on those dates. It is likely that many weeds from these seedbanks would emerge too late to effect serious interference with a fall-seeded canola crop. At harvest, weeds previously selected to mature and shatter seed just before mid May-seeded canola is harvested may not have sufficient time to complete their life cycle and recruit sufficient seeds to the seedbank in fall-seeded canola. Shirtliffe et al. (2000) suggested that harvest timing can be employed as a wild oat management tool in wheat.

The advantage of fall seeding is not because there is something inherently superior about fall seeding versus mid May seeding, but because the weeds will be subjected to operational diversity that leaves them unprepared to compete at the same intensity level as previously. Of course, if all seeding was shifted to an earlier date, weeds would also adapt to that practice. The key is not changing to one favored practice, but combining many different practices into a diverse cropping system to minimize niches left for weeds.

Figure 2. Canola (*Brassica napus*) seeded early November, 1998; late April, 1999; and mid-May, 1999; (left to right). Photo taken on June 26, 1999, Lacombe Research Centre, Lacombe, Alberta (Experiment 99005).

Summary

Buhler (1999) lamented that "we seldom examine the causes of the perpetual presence of weeds". Savory (1988) suggested that weed outbreaks are characteristic of low successional communities. Weed Scientists have done little to confirm or exploit the effects of high successional communities on weeds. Indeed, few of us have looked beyond simple monoculture cropping systems for weed management solutions. There is a need for basic weed biology and ecology research which can provide information that will enable weed suppression by exploiting cropping systems and high successional communities, and the consequences they enforce, in our behalf. A focus on the tactical use of several tools versus individual tools, and on long-term population management versus immediate eradication would increase the integration level of weed management (Cardina et al. 1999). Walker and Buchanon (1982) suggested that not only must IWM have a broader focus than weed control alone, but that it must be integrated with all other crops and crop production practices that influence the ecosystem. Accordingly, it is conceivable that the best thing a grower can do for IWM in canola, may be in another crop.

Despite where IWM in canola seems to be at present, there are indications that IWM adoption will be greater in the future. High input and low output prices, as well as the reality of herbicide resistance have forced growers to look beyond herbicide technology alone for weed management solutions. In Canada, a shift in public attitude from "environmental awareness to environmental action" (Swanton et al. 1991), may also force greater IWM adoption in the future. Refocusing on cultural systems that suppressed weeds before herbicides were available will help us develop IWM practices which include the judicious use of herbicides in an economically and environmentally sustainable manner. Alternative weed management systems "give producers more flexibility and help preserve the effectiveness of herbicides" (Buhler 1999). It is no surprise that many of the cultural and non-chemical options important in IWM cropping systems (Boerboom 1999; Nalewaja 1999; Thill et al. 1994) mirror practices that are advocated for delaying and/or managing weed resistance.

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Challenges of implementation
– a manufacturers' perspective

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Herbicide manufacturers have focused on the judicious use of herbicides, rather than developing integrated weed management (IWM) strategies as a means of reducing herbicide consumption. Manufacturers may appear to be at variance with IWM principles because herbicide rate structures are driven by consistent performance over varying environments and thus may overcompensate for 'normal' growing or spraying conditions. IWM strategies do not fully account for the interaction between crop management, weed complex, and environment in defining optimum herbicide rates. IWM principles are transferable, but specific herbicide recommendations within an IWM context are not easily transferable. Due to industry consolidation and increased farm size, manufacturers must continue to evolve to solution selling. Solution selling has to accommodate the willingness to recommend other products and approaches to manage weeds. Credible information and advice ensures sustainable business relationships between manufacturers', growers and retailers. Underpinning solution selling is the realization that understanding customers' weed management needs requires information on weed biology and other IWM components. For the manufacturer, incorporating weed biology, weed distribution and weed shifts with agronomic practices into economic solutions are increasingly important in meeting the information needs of the client.

Introduction

As we move forward into the new millennium, the industry is facing challenges in three areas. Firstly, manufacturers have diminished credibility due to the lack or incomplete disclosure of information to the public and regulatory agencies. Secondly, politicians untrained in science are arbiters between an increasingly skeptical public and industry; and finally, the public and media untrained in science are inundated with information to sort through and come to an informed opinion.

Given this backdrop, how best to integrate herbicides into an IWM context? In brief, the use of herbicides and development of technology must be included in a broader social context.

Integrated weed management

Integrated weed management (IWM) has many interpretations and understandings, in large part reflective of the varied disciplines participating in weed science (Buhler et al. 2000; Hall et al. 2000). In essence, IWM combines different agronomic practices to manage weeds in order to reduce the reliance of any one weed control technique (Buhler et al. 2000). In addition to the integration of many weed control practices, Buhler et al. (2000) highlights the need to understand the basic weed biology in various management systems as a critical component of IWM.

The primary focus of IWM is on herbicide use and in many cases the primary goal is to reduce herbicide consumption. Although many manufacturers have tried to focus on the judicious use of herbicides, the two approaches are similar yet appear as opposing perspectives. Are they indeed the same? Both are management processes with different degrees of emphasis. Irrespective of the perspective, the interpretations and implementation of IWM must have a single common denominator, economic sustainability.

There are a number of IWM components that manufacturers are directly involved in research and development, but many that we are not involved with. However, all IWM components do have a role to play in weed management, and it is largely left up to research and extension in the public domain to develop various IWM strategies. Table 1 identifies the various IWM components (not a complete list) and the involvement of agchem manufacturers.

Prevention and cultural weed control are not areas of active research, with the possible exception of crop/cultivar selection. Many manufacturers are becoming vertically integrated and have significant breeding operations. Improved yield and vigour are ongoing improvements in germplasm, however, the primary focus is on various input/output traits. Insofar as improved agronomic characteristics in commercial varieties are involved in crop competition, manufacturers are involved in IWM.

Within field assessment, weed thresholds and competition studies are virtually all conducted by public domain research organizations. Although weed surveys are central to understanding weed biology and its interaction with cropping systems, manufacturers are involved indirectly primarily through market research activities.

Table 1. Components of IWM and the involvement of agchem manufacturers.

IWM Component	Manufacturer's Involvement*
Prevention:	
Clean seed	X
Clean equipment	X
Encroachment areas	X
Cultural weed control:	
Crop/cultivar selection	?
Crop rotations	X
Seeding dates/rates	X
Fertilizer management	X
Soil management	X
Physical weed control (tillage, mowing)	X
Field assessment:	
Weed thresholds – relative time to emergence;	X
Density; duration of competition	X
Field scouting:	X
Weed surveys	?
Crop-weed modeling – decision support systems	X
Biological weed control:	
Classical	X
Inundative (mycoherbicides)	?
New discovery leads – natural products	√
Herbicide use:	
New chemistries	√
Formulations – surfactants	√
New mixes of existing actives	√
Improved application delivery	?
Other:	
Elimination of high risk uses	√
Genetic engineering	√
Optimize application timing	√
Rate structure – reduced use rates	√

* X = no manufacturer involvement
? = some or indirect involvement,
√ = manufacturer involvement.

Biological weed control is an area of active research and development, but focussed primarily for new discovery leads and natural product development. The development of mycoherbicides per se is not the main area of focus (Gressel 1992; Zoschke 1994).

Herbicide discovery and new use pattern is still a very active area of research and development. Much development is focussed on new mixes of existing actives due to the cost of developing new chemistries. To reduce herbicide release into the environment the research and development focus is on low rate use chemistries, formulations and surfactants, elimination and replacement of high risk uses (e.g. atrazine mixed with other actives to reduce triazine ground water contamination), revised application timing and rate structure (Zoschke 1994).

Rate structure

In IWM, the use of herbicides and the rate structure employed is one area of intense focus; when to spray and at what rate to spray? What is the optimum rate to spray? What is the impact on rate structure when different active ingredients are combined? Often herbicide effectiveness depends on the application system, the environment and crop/weed density and growth stage. Elucidating the rate structure given these variables is one of the more challenging aspects of herbicide development (Hall et al. 2000; Zoschke 1994).

In the commercial arena, the rate structure typically reflects the widest growth stage window of the most difficult-to-control weed under the widest of environments that still delivers a consistent high level of weed control. Occasionally, rate structures reflect subgroups of differentially susceptible weeds. In the pursuit of consistency over environments and flexibility in use (broadleaf tank mixes, wide growth stage of application, etc.), herbicide rate structures too often overcompensate for the 'normal' growing and spraying conditions. This allows end users to reduce herbicide rates under certain conditions without compromising herbicide performance.

Rate structure (weed thresholds)

Traditionally, IWM has used the concept of weed thresholds to help guide the decision process to spray herbicides or not. However, differing viewpoints on defining weed thresholds has evolved and include economic thresholds; economic optimum threshold; no seed threshold (Buhler et al. 2000; Hall et al. 2000). Each threshold concept increasingly accounts for population dynamics and weed seedbank management. Within an IWM context, herbicide rate structure is typically defined for a specific set of conditions, and is not easily transferable.

Factors not fully accounted for in IWM research and decision support systems include the fact that the weed community is multispecies in nature and that the majority of data is single species. At the field level, the use of data is primarily linear, although that is certainly changing. Weed threshold models ignore the additive or synergistic effect of diverse weed communities when each weed is below its own threshold (Hall et al., 2000). Moreover, the interaction between crop management (seeding date, depth, rate, fertilizer placement and amounts), weed complex and environment impacts the optimum herbicide rate or rate structure.

Rate structure (marketplace)

As product introduction increases, the competitive marketplace can help drive herbicide rate structures to the lowest common denominator. For example, BASF introduced the small grass rate with Poast™ (sethoxydim), in response to the market introduction of quizalofop (Assure™) and clethodim (Select™). Prior to the introduction of these new products, the rate structure was tiered and required 145 g ai ha^{-1} to control green foxtail (*Seteria viridis*), 200 g ai ha^{-1} to control wild oat (*Avena fatua*) and 210 g ai ha^{-1} to control volunteer cereals. The current reduced rate structure incorporates a number of IWM principles. Volunteer cereal and wild oat control is obtained at 145 g ai ha^{-1} (green foxtail rate) provided the herbicide is applied at an earlier weed growth stage (1-4 leaf stage vs. 1-6 previously), growing conditions are good (good soil moisture and fertility and warm temperatures) and that weeds are moderate in density.

Although manufacturers are improving the label rate structure, at what point does herbicide rate refinement reach the law of diminishing returns? Or what may be some of the potential endpoints? One possibility is to register a minimum herbicide rate per individual weed under various conditions. This would allow the producer or agronomic advisor to design custom mixtures to control weeds on a field-specific basis. Even if this was accomplished the research required to reduce the risk of crop injury or unforeseen antagonism with custom designed tankmixes, let alone the crop residue requirements, would be prohibitive. Institutions or individuals would view privately generated research as proprietary and fragment the information flow among the agricultural community.

Also, is the knowledge and recommendation comfort zone (guaranteeing herbicide performance) sufficiently developed among agronomic advisors to recommend the use of reduced rates? Currently, the rate structure allows for some herbicide rate reduction under specific conditions (good growing conditions, moderate weed populations, and small growth stage weeds). Growers and independent crop advisors have recommended reduced herbicide rates in this "comfort zone" with little consequence of herbicide nonperformance. However, manufacturers are continually refining the rate structure and removing the headroom previously ensconced in herbicide labels. New product introductions are less likely to label for the most difficult to control weed and rather add these weeds to the "suppression" category in order to keep the rate structure lower and the range smaller.

Herbicide resistance

Perhaps no other factor has forced industry to consider adapting IWM than the onset of herbicide resistance. Although the economic model has at its core to recoup investment cost as quickly as possible prior to patent expiration, the primary risk and consideration was the entry of generic competitors or new actives in similar markets. This leads to continuous use of the same weed control products.

Herbicide-resistant weeds are "wild cards" in managing product longevity in the marketplace.

This has forced manufacturers to understand the biology and population dynamics of weeds in order to maximize the profitability of herbicides. The significant new consideration is product longevity in the marketplace. This is especially important given the near prohibitive cost of introducing new products. The implications are significant in both current product usage and in product development. This understanding has become a competitive advantage.

The service portion of the marketplace is another venue for IWM practices to take root. For example, wild oat breakthroughs on ethalfluralin-treated fields are serviced with a field call, an assessment of the situation is made, and often a voucher for an alternate mode of action product is issued for spot spray retreatment. This action has reduced the risk of herbicide-resistance development, and practiced no seed threshold (Buhler, 2000).

Solution selling – IWM for manufacturers

Drivers of change in the agricultural industry are many and include: public perception; biotechnology; information technologies; consolidation; and industry maturation. Although biotechnology and public perceptions are significant drivers of change within our business, the discussion will focus primarily on consolidation in agriculture, the maturation of our business, and information generation and use.

Market consolidation

The latest census data (1996) in Figure 1. shows a decline in the number of farms in Canada, but also an increasing size of farm operations. Over the last five years this trend has almost certainly accelerated. With more acres to manage and with less time for decisions, growers are increasingly turning to others for professional agronomic advice. With this development, an increased opportunity exists to incorporate IWM solutions to weed management problems.

To achieve critical mass to fund investment in research and develop technology, many companies or agriculture divisions of companies are consolidating, whether through acquisitions or mergers. This puts in place economies of scale to compete for customers or compete within the marketplace. Many acquisitions have been in biotechnology or seed companies that allow existing agricultural companies to vertically integrate their businesses. Also, the relatively low growth rate in crop protection sales (approximately 2% per year) has caused the spin-off and divestiture of agriculture crop divisions from a number of companies (Figure 2). Much of the driving force behind consolidation is due to the low rate of return compared to the pharmaceutical sectors. Also, the slow public acceptance of genetically modified organisms in agriculture and food has made this sector less attractive for investment. Since 1996 five major mergers or acquisitions in the agchem sector alone has occurred and are outlined in Table 2.

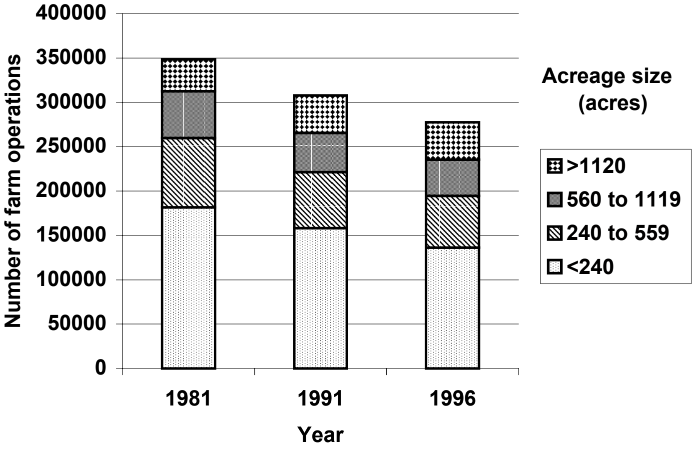

Figure 1. Number of Canadian farms delineated by acreage, 1981-1996.

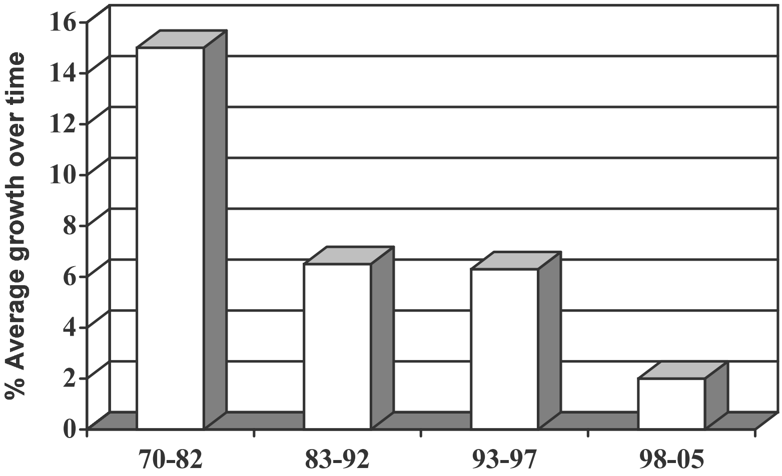

Figure 2. Crop protection sales growth from 1970 – 2005.

Table 2. Industry consolidation from 1996 - 2000.

Merger Partners	**New Entity**
Ciba Geigy + Sandoz	Novartis
BASF + Sandoz U.S.	BASF
Novartis + Merck AG	Novartis
Rhone Poulenc + Agrevo	Aventis
BASF + Cyanamid	BASF
Novartis + Zeneca	Syngenta

As the industry consolidates, product lines within companies increase substantially. This allows for more choice but the consolidated homogenous product lines means greater competition among the manufacturers since they offer like or identical products. For example, five manufacturers are offering glyphosate in Canada in 2000. More choice begets more difficult decisions since product differences are small and product characteristics significantly overlap. Coupled with the increase in farm size and its resultant time constraints, growers will increasingly seek more advice and service.

In the past, and still predominant today, a “best product” model prevails by which companies develop a better product and customers pay a premium. Philosophically, this promotes “one shot” weed control and continued repeat use. With enhanced product portfolios due to consolidation, the industry is better positioned to develop a comprehensive relationship with the grower and offer the best solution to their particular weed/pest problem. The change in thinking is the approach of solving the customers’ broad weed problem where both parties share in the benefit. This is similar to a weed management philosophy.

Solution selling

Manufacturers and other agriculture companies are focussed on relationship building with high value growers and retailers. Part of the relationship building exercise with high value growers involves IWM concepts of field scouting and other agronomic advice. Line companies and retail outlets have agronomists that field scout and prescribe solutions to weed, insect, disease, soil fertility or other agronomic problems. Even sales forces of main agchem manufacturers are following a diagnosis and prescribe approach to weed management.

Instead of prophylactic use of herbicides, herbicide use can be targeted and ultimately a more complete solution prescribed. More importantly, the realization that treating different customers differently is key to optimizing resources and increasing efficiency, a key concept in IWM as well.

In order for solution selling to succeed, understanding customer needs and meeting those needs are key. Of course this may be interpreted in the short term and current selling behavior is maintained. However, the essence of this approach and the key to its success over the long term is to seek solutions that exceed immediate needs and demands. Building a relationship with the customer is best established with credible information and advice. This can and will become a competitive advantage.

Maximizing value by “doing the right thing”. The balance between providing a needed solution and selling a company’s particular product or brand is paramount. Solution selling approach has to accommodate the willingness to recommend other products or approaches. Why? In part, the grower, especially the high value grower, is increasingly knowledgeable. The marketplace is complex and many information sources are available to validate a company’s recommendation. Also, the marketplace is converging. There are fewer manufacturers each with similar product portfolios. All can offer similar solutions. One of the constraints to changing sales behavior is the current reward and recognition program for employees. As long as the predominant factor is strictly increased sales per territory, true IWM solutions will be slow in coming.

Information generation and delivery

A key competitive advantage to any manufacturer is the ability to anticipate customer needs. This concept is not difficult to grasp; it could be a question as simple as "What are today's secondary weeds that will become tomorrow's primary weeds? 1-800-information lines are increasingly being used as data sources beyond strict product information. The information database this generates is very useful to be proactive, not reactive. What weeds are important to you? What are your top five weeds? What weeds are you noticing for the first time? What production system are you currently using? What crops are you growing in rotation?

To anticipate tomorrow's solutions, one needs a fundamental understanding of the agriculture landscape. Underpinning any IWM is the basic understanding of weed biology in various management systems. Quite simply, weed surveys are paramount in identifying weeds worthy of study and economic focus. What weeds are growing and where? What weed complexes or spectra are associated by region or production system? Why are herbicides apparently used in fields on weeds that do not appear on the product's label? Or are not controlled very well? What individual weeds in the weed complex drive producers' purchase decision? What weeds in that complex will drive his purchase decision tomorrow? Do we as a manufacturer have a current solution? Can we develop a solution for him tomorrow? Can we provide value in the interim? How do we bring all information to some common understanding and implementation?

Challenges of implementation

Herbicides are a key component of integrated weed management programs. As members of the larger community we must address public and regulatory concerns with herbicide use. Continued research into weed biology and population dynamics of weeds in different production systems must be supported in order to understand and implement IWM. Weed and related surveys are an important first step in IWM. Increasing our understanding of herbicide resistance development and management under different production systems will help insure product longevity, both current and future products.

A better utilization of information currently in the public domain is needed. Integrating weed biology and utilizing the four windows of spray application to create weed management solutions is currently available for many weeds. Manufacturers and others need to continue to evolve towards solution selling. As consolidation continues, future crop input decisions will become more integrated. Solution selling ensures the economic sustainability of producers and all stakeholders, the true competitive advantage.

Information has become proprietary, a somewhat unfortunate consequence of increased market competition, value profiling, and repositioning in agriculture. The Expert Committee on Weeds is uniquely positioned to lead discussion, to coordinate research, and to disseminate information on IWM among all stakeholders. It is important that all stakeholders remain engaged. The Expert Committee on Weeds can provide that forum.

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Integrated weed management
– making it work on your farm

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Introduction

This is a brief description of how I implement integrated weed management on my farm, located close to Biggar, Saskatchewan. Soil conservation and our move drove our changes in management practices to a direct seeding system and our need for cost-effective weed control. We strive for diversity in crops and herbicides because weeds thrive with repetition. In addition to rotation, we use a wide range of techniques, including sanitation of field edges, and low cost field maps for spot treatments of weeds. Our main concern is our reliance on glyphosate and the potential for selection of glyphosate resistant weeds.

This paper will explain the two fundamental constraints that dictate my farm practices. I will then discuss the integrated weed management (IWM) implications of residue management, seeding practices, fertilizer placement, and crop/herbicide rotations. I will explain how I integrate these factors in a strategy that favors the crop while discouraging weed growth. I will also discuss strategies to enhance herbicide efficiencies as well as the advantages of field mapping and record keeping. Lastly, I will indulge in speculation of future strategies and try to identify future problems and challenges.

Before I discuss integrated weed management on my farm, it is necessary to recognize the constraints: one philosophical and the next financial.

My wife, Shirley, and I have farmed the dark brown soils in the Bear Hills south of Biggar, Saskatchewan for more than twenty-five years. We realized the greatest threat to sustainable agriculture is soil degradation. First-hand experience with wind and water erosion and the need to maximize water use efficiency set us on the path to reduced and finally zero-tillage. Soil stewardship is our philosophical constraint as we address integrated weed management.

If I use current (2000) commodity prices and crop insurance average yield data, I can expect gross returns of approximately $125 per acre for cereals, peas, and canola. Clearly cost effectiveness is the second constraint to weed control, which leads to integrated weed management as a cost-effective strategy.

Crop competition is the cheapest and best tool in an IWM strategy.

Whatever farmers do should benefit the crops they grow and hopefully discourage weed production.

Residue management

Combines can play a role in weed management. Proper combine clean-out can minimize moving weed seeds and species between fields. Properly adjusted straw and chaff spreaders will leave weed seeds on the soil surface and expose these seeds to cycles of sunlight and rain and can reduce viability. This strategy can also reduce competition from volunteers the following year. This is especially true for malting barley (*Hordeum vulgare* L.) varieties that will germinate quickly when wet but will likely not establish roots quickly enough to survive when the surface dries. Wild oats (*Avena fatua* L.) also lose their dormancy potential if left on the surface.

Seeding practice

If you can get a healthy crop out of the ground before the weeds, the crop usually wins. Seeding is a very important feature in the IWM toolbox. You want to bury, pack, and fertilize the crop you want to grow not the weeds. The more soil disturbance at seeding, the greater the weed pressure. This principle is demonstrated by comparing the density of weed populations in tilled fallow compared to chemical fallow. However, there can be trade-offs. A high disturbance seeding system (sweeps or discers) can kill winter annuals but will increase annual weed densities.

On-row packing will encourage germination and emergence of the crop but not the weeds. Random packing, like harrow packer bars, is friendly to both weeds and crops. Again, low-disturbance seeding with on-row packing will favor the crop you are trying to grow over the weeds you want to avoid.

Nutrient management

Rates, timing, and placement of fertilizer can have an impact on weed management. The object is to supply nutrients to the crop and to starve the weeds. To accomplish this, the seed drill needs to be the nutrient applicator. I try to place my fertilizer blend within an inch of the seed and I can accommodate this with a paired row system. My drill has shanks that places the fertilizer between two seed rows, three inches apart. This means that any weeds that originate between shank rows are at a disadvantage in accessing nutrients and the crop should win.

If you have no option but to place fertilizer with the seeds, keep in mind that there is a high risk of seedling damage which reduces seedling vigor and places the crop at a disadvantage in competing with weeds.

Crop and herbicide rotation

Crop and herbicide rotation is unquestionably the most important tool in IWM. This strategy involves varying the crop grown, the herbicides used, and the timing of seeding, harvest and herbicide application. Rotation assists marketing, disease control, herbicide resistance, and thus provides cost efficiency. For this paper, only herbicide resistance and cost efficiency will be discussed.

Weed species thrive with repetition. Epidemic weed problems are usually created over several years by a system which favors a weed species. A good rotation should provide enough diversity to discourage weed selection. Rotation should allow us to select low cost herbicides to address problems. Canada thistle and perennial grass can be controlled in canola more effectively and cheaply with a pre-harvest application of glyphosate in a cereal crop the year before the canola is seeded than in-crop with Lontrel® (clopyralid) and Poast® (sethoxydim).

Broadleaf weed control is cheap and easy in a cereal crop. Grassy weeds are controlled best in broadleaved crops. When you design your rotations, always consider the current crop as a potential volunteer problem and use your rotations to deal with problems you anticipate may appear. Rotations need to be flexible to adapt to weed and market changes.

Crop 1 is a pulse crop which is seeded first, before crops 2, 3 and 4. I often use a broadcast unincorporated ethalfluralin in the fall or early spring here. I try to apply the burn-down just prior to crop emergence and possibly an MCPA sodium salt and Sencor® post emergence with the option of in-crop grassy weed control. If you need all the herbicide treatments and get a less than an average crop, buying groceries could be a real challenge.

A little 2, 4-D before freeze up will control winter annuals. This will set you up for a crop of hard red spring wheat the next year with the nitrogen from the pulse boosting the wheat protein.

Crop 2 is sown second and would be a cereal probably barley or CPS wheat (both need early seeding dates) seeded on canola stubble. Neither need the protein boost of the pulse stubble and the canola volunteer is easy to control. I try to apply the burn-off herbicide just prior to emergence. The nutrient placement should give the crop a competitive advantage over grassy weeds and limit in-crop application to a broadleaf herbicide with, at most, patch spraying for wild oats. Pre-harvest glyphosate is an option for grassy weeds or Canada thistle (*Cirsium arvense* L.).

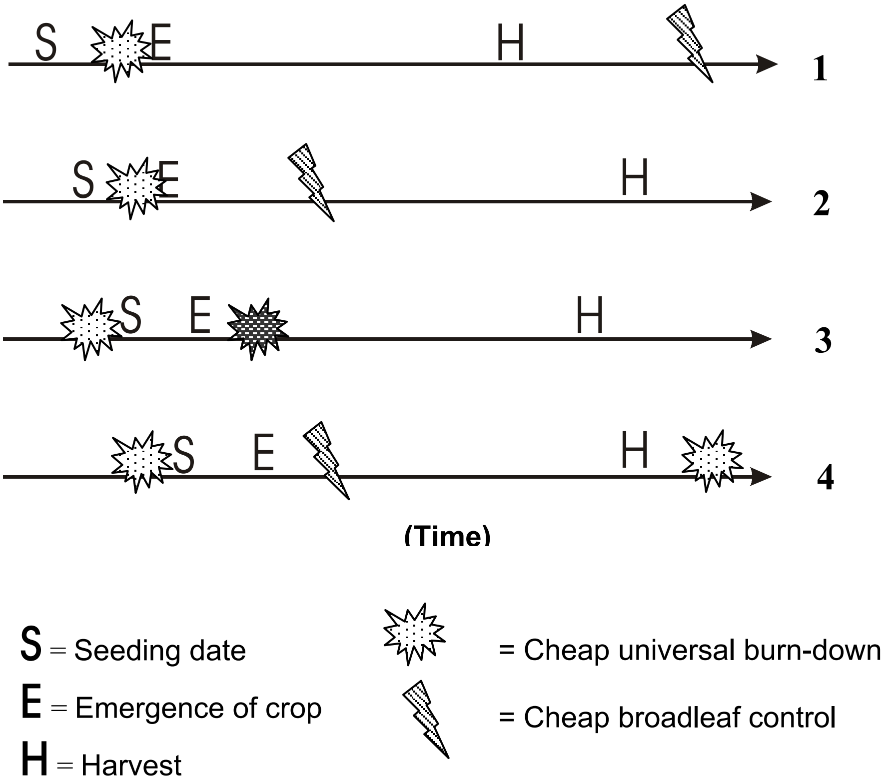

Figure 1. Diagram of the basic rotations over four years and the sequence of farm operations over the cropping system.

Crop 3 is sown next and is an oilseed canola (*Brassica* spp.) or flax *(Linum usitatissimum*) depending on markets. If it is a herbicide tolerant variety it would be a Liberty Link® variety. This is the least effective herbicide option and needs a tank mix of Fusion® (fenoxaprop-p-ethyl, fluazifop-p-butyl) or Select® (clethodim) for volunteer barley. My farm is too dependent on glyphosate as it is, and I find Monsanto's Technology Use Agreement unpalatable so I do not use Roundup Ready® canola. I had significant reduction in wheat yield following Odyssey®. These serious residual problems mean the Pursuit "Smart"® systems are not an option on my farm; I try to avoid any herbicides that have cropping restrictions.

If this were flax, the post emergence herbicide would be a Buctril®/Poast (bromoxynil MCPA/sethoxydim) tank mix. Either would have a pre- or post-harvest spray option.

Crop 4, the last to be seeded, would be my hard red spring wheat. Since the winter annuals were dealt with a post-harvest 2, 4-D, we should not have much except grassy weeds and small annuals to deal with even though it is later in May.

I will likely use a glyphosate/2, 4-D amine tank mix for burn-down and hope the residual 2, 4-D will favor the crop in its early stage. There are a host of in-crop options for broadleaved weed control and hopefully the nutrient management and low disturbance will have addressed annual grassy weeds. Again, we have pre- and post-harvest options for herbicide application.

Fall seeded cereals and canola would be great additions to a rotation but the ultimate rotations would include forages. As an IWM tool this could address the weed seedbank in a very positive manner.

Efficiencies

Good field margin sanitation can prevent grasses and other weeds from encroaching. I will often spray the field margins and cultivate a twelve-foot perimeter. In addition to controlling weeds and grass encroachment, this provides a fireguard.

My drill has two offset shank rows to provide a tramline marking system and my sprayer covers exactly three widths of the drill. This eliminates unnecessary overlap saving both money and time.

I have field maps drawn from aerial photographs (Figure 2). They have several uses. These maps are carried in the tractor and combine during seeding, spraying, and harvest. During spraying, I use them to identify wild oat and other problem weed patches for future spot spray applications. It is a low technology, low cost precision farming application that works.

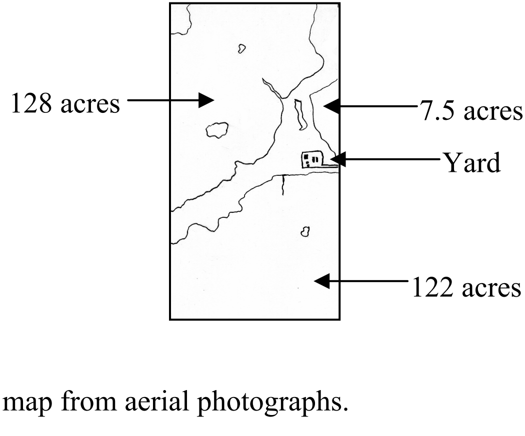

Figure 2. Field map from aerial photographs.

Figure 3. Silver Bull'et weed control and antidote.

Future strategies

IWM could benefit greatly from weed seed removal methods like chaff collection or the McLeod Harvest System®. Swathing could become a weed management tool if it would get weed seeds into the combine and that weed seed collected and removed with the chaff.

Tillage could be part of a rotation and an IWM tool. I am considering a tillage operation every eight years as a method of reintroducing granular Treflan® (trifluralin) and Avadex® (triallate) back into my rotation. Likely, I would broadcast a fertilizer, canola, and granular mix in the spring and incorporate it with a tandem disc and a harrow packer drawbar. This would limit the exposure to erosion, smooth the fields and introduce a different herbicide group. The next crop would be barley to take advantage of its Treflan® (trifluralin) tolerance and residual weed control. This strategy would also address the tartary buckwheat problems that come with glyphosate intensive systems.

Future concerns

I am very concerned with the development of Round-up Ready® wheat. If it is introduced, the zero-till system I have worked so hard to make succeed would be jeopardized. Glyphosate tolerant cereals as a volunteer, at a minimum, add a huge expense that farmers should not be expected to assume. Our farm could not absorb the cost.

One scientist I spoke with said, “All zero-tillers live in fear of the glyphosate tolerant weed that will defeat their system. Why would we invent one and sell it to them.” Australia has severe problems with glyphosate tolerant rye grass that is also resistant to all other grassy weed herbicides. Do we need to tempt fate? Regrettably, as farmers we must ultimately deal with the consequences of these decisions.

Integrated weed management
– a retail agronomist's perspective

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A retail agronomist has a unique perspective of integrated weed management (IWM). It is strongly influenced by the views of producers and other retailers and is very practical in nature. Producers practice varying degrees of IWM as a necessary part of their crop production systems. Most operations, however, have room to adopt additional components of IWM. Many retailers view it as a business growth opportunity. Providing information on IWM profiles retailer knowledge and represents an additional service that should develop client loyalty and assist with long-term growth of the retail.

Introduction

As a retail agronomist I have two main types of clients, producers and retailers, who influence my perspective of integrated weed management. I work closely with producers, scouting fields and making weed control recommendations as well as assisting with overall crop planning and agronomic problem solving. I also work closely with Agricore retail staff, providing agronomic training and acting as a resource for technical information. I believe my relationship with these two groups of people gives me a realistic view of integrated weed management at the farm level.

Key questions

I will present my perspective of integrated weed management (IWM) by answering three key questions.

1. Do producers practice IWM?
2. How do producers perceive IWM?
3. What does IWM mean to a retailer?

Do producers practice IWM?

I believe the short answer to this question is yes. The more important aspect of the question is to what degree. Integrated weed management has been defined as a combination of "different agronomic practices to manage weeds, so that the reliance on any one weed control technique is reduced" (Kelner et al., 1996). The ideal IWM system might combine a dozen identifiable agronomic practices for managing weeds. In reality, most producers are only using a handful of practices that might be considered components of IWM.

Producers understand that good crop management means good weed management. Agronomic practices required to produce a good crop are inherently good weed management strategies as well. Some examples of commonly used IWM strategies include:

a) Strategic seed placement and seedbed management which hastens crop emergence and crop competitive ability.
b) Selection of competitive crop varieties (eg. certain hybrid varieties of canola).
c) Delayed seeding of oats and flax combined with pre-seed burn-off or tillage to help manage wild oats.

Most producers are using some of the elements of IWM as part of their crop production strategy. There is certainly room for the adoption of additional IWM practices in many operations.

How do producers perceive IWM?

Producers think in the context of crop production, of which weed control must be a component. Most producers would struggle to identify the specific components of integrated weed management, but the practices they use to produce a good crop would certainly qualify as components of IWM. Weed control is seldom the first priority in crop planning, although it almost always ranks near the top. Crop rotations and commodity prices are the major factors dictating crop selection. Weed management strategies are usually adjusted to meet these overriding priorities.

For example, a weed management extensionist might describe winter wheat as an excellent crop choice as part of a weed management strategy. Its winter annual growth habit helps offset weed life cycles and reduces the need for wild oat herbicides which might, in turn, reduce the selection pressure for weed resistance. Producers may also consider winter wheat an excellent crop choice for slightly different reasons. Producers might view winter wheat as a crop that offers similar returns to spring wheat while distributing the workload, spreading out the risk of fusarium infection and allowing them to get away from spraying wild oats for a year. Understanding these small differences in perception can help weed extensionists and researchers deliver their messages more effectively.

Having said that, at some point weed control does become a primary factor in crop planning. In preventative situations, where fields are relatively clean and weeds are not restricting crop production, producers are not likely to modify their current weed control program. In curative situations, where weeds have already become a management issue hindering crop production, producers will readily seek and adopt new management strategies because the status quo is no longer working. A classic example of this is weed resistance and herbicide rotation. Producers are less likely to adopt herbicide rotation until they have first hand experience with resistance, observing it or suspecting it on part of their farm.

What does IWM mean to a retailer?

Most of today's retailers pride themselves on their service. Producers rely on their retailers' advice and many retailers have to gone to great effort to ensure they are qualified to provide this advice (eg. Certified Crop Advisor Program). Retailers want to be viewed as a source of high quality agronomic information, realizing that good information helps close the sale.

Retailers view integrated weed management through the eyes of their clients. They see it in the context of crop production and the overall farm operation and not as a set of independent practices. Retailers routinely make weed control recommendations that would be considered components of IWM although they probably would not identify their recommendations with IWM. Examples of retailer IWM recommendations include:

a) No spray recommendations where weed densities and relative staging warrant it.
b) Herbicide rotation recommendations based on herbicide use history.
c) Weed management strategies to accompany specific crops (eg. Edge, tillage, pre-seed weed control for sunflowers).
d) Advice on variety selection (eg. certain hybrid canola varieties help with weed competition).
e) Advice on special weed problems (eg. herbicides plus tillage for severe dandelion problems).

Despite good intentions retailers are constantly faced with the pressure of meeting short-term sales objectives. These objectives are sometimes in conflict with the goals of integrated weed management, which is ultimately to reduce the reliance on any one weed control technique, usually herbicides. However, most retailers realize that a good recommendation on one field will likely buy the business on other parts of the farm as well as gain long-term loyalty and a good reputation.

Most retailers are in business for the long term and are willing to sacrifice a single sale in exchange for long-term business growth. Integrated weed management offers an opportunity for retailers to demonstrate that their knowledge expands beyond input products. It represents an opportunity to build their business through better information and service.

Literature cited

Kelner, D., L. Juras, and D. Derksen. 1996. Integrated Weed Management – Making it Work on Your Farm. Manitoba Agriculture and Saskatchewan Agriculture and Food.

Annex 1

Common and chemical names of herbicides

Common Name	**Chemical Name**
2,4-D	(2,4-dichlorophenoxy)acetic acid
atrazine	6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine
bromoxynil	3,5-dibromo-4-hydroxybenzonitrile
chlorsulfuron	2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide
clethodim	(E,E)-(±)-2[1[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one
clopyralid	3,6-dichloro-2-pyridinecarboxylic acid
dicamba	3,6-dichloro-2-methoxybenzoic acid
dichlorprop	(±)-2-(2,4-dichlorophenoxy)propanoic acid
diclofop	(±)-2-[4-(2,4-dichlorphenoxy)phenoxy]propanoic acid
difenzoquat	1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium
diquat	6,7-dihydrodipyrido[1,2-α:2′,1′-*c*]pyrazinediium ion
diuron	*N*′-(3,4-dichlorophenyl)-*N*,*N*-dimethylurea
ethalfluralin	*N*-ethyl-*N*-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine
ethametsulfuron	2-[[[[[4-ethoxy-6-(methylamino)-1,3,5-triazin-2-yl]amino]carbonyl]amino]sulfonyl]benzoic acid
fenoxaprop	(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid
flamprop	*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-*DL*-alanine
fluazifop	(±)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid
fluazifop-p	(*R*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid
glufosinate	2-amino-4-(hydroxymethylphosphinyl)butanoic acid
glyphosate	*N*-(phosphonomethyl)glycine
haloxyfop	(±)-2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid
imazamethabenz	(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-4(and 5)-methylbenzoic acid (3:2)
imazethapyr	-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid
linuron	*N*′-3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea
MCPA	(4-chloro-2-methylphenoxy)acetic acid
mecoprop	(±)-2 -(4-chloro-2-methylphenoxy)propanoic acid
metribuzin	4-amino-6-(1,1-dimethylethyl-3-(methylthio)-1,2,4-triazin-5(4*H*)-one

metsulfuron	2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoic acid
paraquat	1, 1′-dimethyl-4-4′-bipyridinium ion
picloram	4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid
prometryn	*N, N′*-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine
pronamide	3,5-dichloro (*N*-1,1-dimethyl-2-propynyl)benzamide
quinclorac	3,7-dichloro-8-quinolinecarboxylic acid
quizalofop	(±)-2 –[4-[(6-chloro-2-quinoxalinyl)oxy]phenoxy]propanoic acid
sethoxydim	2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one
simazine	6-chloro- *N, N′*-diethyl-1,3,5-triazine-2,4-diamine
thifensulfuron	3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid
tralkoxydim	2-[1-(ethoxyimino)propyl]-3-hydroxy-5-(2,4,6-trimethylphenyl)-2-cyclohexen-1-one
triallate	*S*-(2,3,3-trichloro-2-propenyl) bis(1-methylethyl)carbamothioate
triasulfuron	2-(2-chloroethoxy)-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide
trifluralin	2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzenamine

Annex 2

Common and scientific names of crops and weeds

Common Name	**Scientific Name**
alfalfa	*Medicago sativa* L.
annual rye grass	*Lolium rigidum* Gaudin
apple	*Malus pumila* Mill.
Argentine canola	*Brassica napus* L.
ball mustard	*Neslia paniculata* (L.) Desv.
barley	*Hordeum vulgare* L.
black grass	*Alopecurus myosuroides* Huds.
black mustard	*Brassica nigra* (L.) W. D. J. Koch
buckwheat	*Fagopyrum esculentum* Moench
Canada thistle	*Cirsium arvense* (L.) Scop.
canola	*Brassica* spp.
carrot	*Daucus carota* L.
chick pea	*Cicer* spp.
clover, arrowleaf	*Trifolium vesiculosum* Savi
clover, berseem	*Trifolium alexandrinum* L.
clover, Persian	*Trifolium resupinatum* L.
clover, subterranean	*Trifolium subterraneum* L.
common chickweed	*Stellaria media* (L.) Vill.
common groundsel	*Senecio vulgaris* L.
common hempnettle	*Galeopsis tetrahit* L.
common lambsquarters	*Chenopodium album* L.
common ragweed	*Ambrosia artemisiifolia* L.
corn	*Zea mays* L.
cotton	*Gossypium hirsutum* L.
crested wheat grass	*Agropyron cristatum* (L.) Gaertn.
dahurian wild rye	*Elymus dahuricus* Turcz.
dandelion	*Taraxacum officinale* G. H. Weber ex Wiggers
dog mustard	*Erucastrum gallicum* (Willd.) O. E. Schulz
downy brome	*Bromus tectorum* L.
edible bean	*Phaseolus vulgaris* L.
false cleavers	*Galium spurium* L.
field pea	*Pisum sativum* L.
field pennycress	*Thlaspi arvense* L.
flax	*Linum usitatissimum* L.
foxtail barley	*Hordeum jubatum* L.
giant foxtail	*Setaria faberi* Herrm.
goose grass	*Eleusine indica* (L.) Gaertn.
grapes	*Vitis vinifera* L. subsp. *vinifera*
green foxtail	*Setaria viridis* (L.) P. Beauv.
green pigweed	*Amaranthus powellii* S. Watson

green smartweed	*Polygonum scabrum* Moench
hemp	*Cannabis sativa* L.
hood canary grass	*Phalaris paradoxa* L.
horseweed	*Conyza canadensis* (L.) Cronquist
Indian hedge mustard	*Sisymbrium orientale* (L.) Scop.
Indian mustard	*Brassica juncea* (L.) Czern.
intermediate wheat grass	*Agropyron intermedium* (Host) Beauv.
jointed goat grass	*Aegilops cylindrica* Host
kochia	*Kochia scoparia* (L.) Schrad.
lupin	*Lupinus* spp.
narrow-leaved hawk's-beard	*Crepis tectorum* L.
oats	*Avena sativa* L.
perennial sow-thistle	*Sonchus arvensis* L. subsp. *arvensis*
Polish canola	*Brassica rapa* L.
quack grass	*Elytrigia repens* (L.) Desv. Ex B. D. Jacks
redroot pigweed	*Amaranthus retroflexus* L.
rice	*Oryza sativa* L.
rigid ryegrass	*Lollium rigidum* Gaudin
Russian thistle	*Salsola kali* L. subsp. *ruthenica* (Iljin) Soó
Russian wild rye	*Psathyrostachys juncea* (Fisch.) Nevski
rye	*Secale cereale* L.
sea lyme grass	*Leymus arenarius* L.
shepherd's-purse	*Capsella bursa-pastoris* (L.) Medik.
sorghum	*Sorghum bicolor* L. Moench
soybean	*Glycine max*. (L.) Merr.
spiny annual sow-thistle	*Sonchus asper* (L.) Hill
strand-wheat-native	*Leymus mollis* Trin
strand-wheat-naturalized	*Leymus arenarius* (L.) Hochst
sugar cane	*Saccharum officinarum* L.
sunflower	*Helianthus annuus* L.
sweet clover	*Melilotus officinalis* Lam.
tall wheat grass	*Elymus elongatus* (Host) Runemark subsp. *ponticus* (Podp.) Melderis
tartary buckwheat	*Fagopyrum tataricum* (L.) Gaertn.
triticale	*Triticosecale* spp.
vetch	*Vicia* spp.
Virginia pepperweed	*Lepidium virginicum* L.
wheat	*Triticum* spp.
wild buckwheat	*Polygonum convolvulus* L.
wild carrot	*Daucus carota* L.
wild mustard	*Sinapis arvensis* L.
wild oat	*Avena fatua* L.
wild radish	*Raphanus raphanistrum* L.
winter wheat	*Triticum aestivum* L.
winter wild oats	*Avena ludoviciana* Durieu

Index

Considerable research has been focused recently on developing biologically and economically robust integrated weed management (IWM) systems. Growers are increasingly interested in IWMs because of the escalating problem of herbicide resistant weeds, low commodity prices, and rising unease with the environmental and human health effects of pesticides. However, grower interest has not translated into widespread adoption of IWM systems. Of the numerous reasons for slow adoption of IWM most relate to avoidance of real or perceived risk. Farmers are concerned that changing management practices to implement IWM systems will reduce crop production or income and result in greater densities of troublesome weeds. This concern is compounded by the need for short-term profitability in the present economic climate. Farmers are understandably reluctant to accept reduced income or to forego income in one year, even if it means increased income in subsequent years.

There is a clear need for greater discussion on the extent and limitations of current knowledge of IWM systems, and how best to communicate that knowledge to the agricultural community. Thus, the Expert Committee on Weeds - Comité d'experts en malherbologie (Canada) hosted a symposium entitled *Integrated Weed Management: Explore the Potential* at their annual meeting in November, 2000. This monograph contains the papers presented at that symposium.

We hope the reader finds the information in this monograph to be thought provoking. There remains much work to be done by all members of the agricultural community to facilitate widespread adoption of IWM in the near future. Collectively, we can meet the challenge.

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